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AN ELECTROSTATIC PRECIPITATOR SYSTEMS STUDY

Final Report To

THE NATIONAL AIR POLLUTION CONTROL ADMINISTRATION
Cincinnati, Ohio

Contract CPA 22-69-73

SOUTHERN RESEARCH INSTITUTE
2000 9th Avenue S. Birmingham, Alabama 35205

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Southern Research Institute
Birmingham, Alabama
October 30, 1970
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FOREWORD

This report is a summary of the work performed under Contract CPA 22-69-73 by Southern Research Institute. The program was administered under the direction of the Division of Process Control Engineering, National Air Pollution Control Administration, with Mr. Timothy W. Devitt serving as project officer.

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TABLE OF CONTENTS

The report

Page No.

INTRODUCTION.. 1

LITERATURE SURVEY AND PREPARATION OF THE BIBLIOGRAPHY.. 2

REVIEW ~~OF~~ THE STATUS OF PRECIPITATOR TECHNOLOGY.. 5

Descriptive summary of review of precipitator fundamentals 5

and the

APPLICATION OF ELECTROSTATIC PRECIPITATORS IN INDUSTRIAL DUST CONTROL.. 25

The industries mentioned include

Cement, ... 26
Pulp and paper, ... 26
Magnesia, ... 26
Phosphorus, ... 28
Lime 28
Gypsum, ... 28
Sulfuric acid, ... 28
Petroleum, ... 28
Iron and steel, ... 28
Electric power generation, ... 28
Nonferrous metals, ... 29
and Incinerators. 29
Data sources 29
Descriptive summary of application of electrostatic precipitators in major application areas 29

RESEARCH AND DEVELOPMENT RECOMMENDATIONS 54

BASIC RESEARCH PLAN.. 58

REVIEW OF SPECIFICATION AND CONTRACTING PRACTICE 64

LIST OF TABLES

Table No.		Page No.
1	Sources Searched for Preparation of Bibliography of Precipitator Literature........................	3
2	A Survey of the Use of Electrostatic Precipitators in Various Industries............................	27
3	Research and Development Plans	55

AN ELECTROSTATIC PRECIPITATOR SYSTEMS STUDY

Introduction

This is the final report under Contract CPA 22-69-73 covering the systems study of electrostatic precipitators. Work under this contract was performed during the period from April 15, 1969 to September 30, 1970.

The purposes of this program have been: (1) to identify and assess the status of electrostatic precipitator technology, (2) to define current practices in the application of electrostatic precipitators for air pollution control, (3) to identify new potential areas of application of electrostatic precipitation, (4) to investigate existing electrostatic precipitator systems, and (5) to define research and development areas needed to improve the performance of electrostatic precipitators.

The results of this study are presented in a series of documents which, in addition to the final report, include:

(1) a comprehensive bibliography of electrostatic precipitator literature,

(2) a selected bibliography prepared from the comprehensive bibliography which includes the more pertinent articles in the literature (this selected bibliography has been indexed by keyword descriptions for rapid reference to articles covering a given subject), and

(3) a manual of precipitator technology covering fundamentals of electrostatic precipitator technology and the application of precipitators to the control of dust emissions in each of nine major application areas.

The program has been a cooperative effort between Research-Cottrell, Inc., Rust Engineering Co., and Southern Research Institute. Dr. Harry J. White, Head of the Department of Applied Science, Portland State College, Portland, Oregon, has served as consultant to SRI throughout the program. Research-Cottrell has provided the comprehensive bibliography of the literature, the keyword descriptors for the selected bibliography, and data on cost and application of electrostatic precipitators for various types of dust control systems. Rust Engineering has provided information on the application of electrostatic precipitators in the pulp and paper industry. Dr. White has assisted in the review of the fundamentals of precipitator operation and in the review of the data on precipitator performance in the major application areas.

This report is broken down into topics covering the major areas investigated during this program. It covers primarily the methodology of carrying out the program and a summary of the results which are covered in the other documents.

Literature Survey and Preparation of the Bibliography

Organization of the literature survey included searching of specific technical information sources by SRI, followed by a more comprehensive search by Research-Cottrell.

The literature review was first prepared covering the major sources likely to contain articles on precipitators or related subjects. A list of the sources searched is shown in Table 1. The search covered the period from the initiation of the abstracting service to June 1969.

From the gross bibliography, a selection was made of articles containing significant precipitator data as judged by the journal, author, and title of the paper. From the 3000 entries in the original bibliography, about 1000 were selected as being of lasting or timely interest. Each of the articles in the selected bibliography was provided with descriptors selected from a thesaurus of about 100 items. The articles, with their descriptors, were arranged for computer access by keyword.

The bibliography was arranged alphabetically by author and numbered sequentially. In the back of the bilbiography, all of the descriptors comprising the thesaurus were listed with numbers corresponding to the articles for which the particular descriptor is appropriate. In this way, the articles covering a particular subject can be retrieved without the necessity for access to the computer.

Table 1

Sources Searched for Preparation of Bibliography of Precipitator Literature

1. Air Pollution Control Association Abstracts.
2. Electrical and Electronics Abstracts (Science Abstracts, Series B).
3. Physics Abstracts (Science Abstracts, Series A).
4. Chemical Abstracts (foreign).
5. Nuclear Science Abstracts.
6. Index to Publications of The Iron and Steel Institute.
7. Fuel Abstracts and Current Titles.
8. Engineering Index.
9. Applied Science and Technology Index.
10. British Technology Index.
11. Research-Cottrell Technical Information Center.
12. British Coal Utilization Research Association - Monthly Bulletin (foreign).
13. Air Pollution Titles.
14. Reprint collection of M. Robinson.
15. Bibliography on Aerosols, 1950-1955, W. J. Sheffy, supplement to AEC Report SO-10003, 1956.
16. Bibliography on Aerosols, R. A. Stehlow, AEC Report SO-1003, 1951.

17. Bibliography of Selected Articles on Electrical Precipitation, Anon., Cement Mill and Quarry **16**, 18 (Feb. 20, 1920).

18. Southern Research Institute Bibliography derived from:

    a) Air Pollution Technical Information Center,
    b) Defense Documentation Center,
    c) Pennsylvania State University Center for Environmental Studies, and
    c) National Aeronautics and Space Administration.

19. Bibliography of Chapter 5, Air Pollution Control, W. Strauss, ed., New York, in press.

20. Bibliography of Handbuch der Staubtechnik, W. Koglin, ed., Maschinenfabrik Beth, Lübeck, Germany (foreign).

21. Bibliography of Industrial Electrostatic Precipitation, H. J. White, Addison-Wesley, Reading, Mass., 1963.

22. Bibliography of Electrostatyczne Odpylanie Gazow, J. Lutynski, WNT, Warsaw, 1965 (foreign).

23. Bibliography of Ochistka Promyshlennykh Gazov Elektrofiltrami, V. N. Uzhov, Gaskhimizdat., Moscow, 1967 (foreign).

24. Bibliography of An Introduction to Electrostatic Precipitation in Theory and Practice, H. E. Rose and A. J. Wood, Constable, London, 2nd ed., 1966.

25. Bibliography of Sanitary Protection of Atmospheric Air, V. N. Uzhov, Medgiz, Moscow, 1955 (foreign).

26. Bibliographies of numerous papers on electrostatic precipitation.

Review of the Status of Precipitator Technology

To accomplish the objectives of assessing the status of engineering technology on electrostatic precipitators, a review of the literature covering precipitator fundamentals was made. In addition, visits were made to discuss the current research in the area of electrostatic precipitation. These visits included laboratories in the U. S. and in Europe to review work in some of the areas where the status of technology has not been clearly defined.

Details of the review of precipitator fundamentals are covered in the section of the manual covering the various topics of particle charging, corona generation, dust removal, resistivity, etc. The following is a descriptive summary extracted from the manual which describes the major topics reviewed.

Descriptive summary of review of precipitator fundamentals

Electrostatic precipitation utilizes the forces acting on electrically charged particles in the presence of an electric field to effect the separation of solid or liquid aerosols from a gas stream. In the precipitation process, dust suspended in the gas is electrically charged and passed through an electric field where electrical forces cause the particles to migrate toward the collection surface. The dust is separated from the gas by retention on the collection electrode and subsequently removed from the precipitator. Various physical configurations are used to accomplish these basic functions of charging, collection, and removal, depending upon the type of application and properties of the dust and gas.

While particles in a gas stream normally have a small inherent electric charge, it is orders of magnitude too small for effective electrostatic collection. Consequently, the precipitation process must provide a means for particle charging. In all commercial precipitator applications, the charging is accomplished by means of a high-voltage, direct-current corona.

Corona generation. Corona, as applied to electrostatic precipitators, is a gas discharge phenomenon associated with the ionization of gas molecules by electron collision in regions of high electric field strength. The process of corona generation requires a nonuniform electric field, which is obtained by the use of a small diameter wire as one electrode and a plate or cylinder as the other electrode. The application of a high voltage to this electrode configuration results in a high electric field near the wire. The electric field decreases inversely with the radius from the wire surface.

The corona process is initiated by the presence of electrons in the high field region near the wire. Electrons for corona initiation are supplied from natural radiation or other sources and, since they are in a region of high electric field, they are accelerated to high velocities and possess sufficient energy so that on impact with gas molecules in the region, they release orbital electrons from gas molecules. The additional free electrons are also accelerated and enter into the ionization process. This avalanche process continues until the electric field decreases to the point that the electrons released do not acquire sufficient energy for ionization.

Within the region defined by the corona glow discharge, where ionization is taking place, there are free electrons and positive ions resulting from electron impact ionization. The behavior of these charged particles depends upon the polarity of the electrodes, and the corona is termed negative corona if the discharge electrode is negative, or positive corona if the discharge electrode is positive. Both positive and negative corona are used in industrial gas cleaning applications; however, the negative corona is most prevalent within the temperature range of most industrial applications.

In the case of the negative corona, positive ions generated in the corona region as a result of electron impact are attracted toward the negative wire electrode and electrons toward the positive plate or cylinder electrode. Beyond the corona glow region, the electric field diminishes rapidly, and if electronegative gases are present, electrons will be captured by the gas molecules on impact. The negative ions thus generated move toward the collection electrode and serve as the principal means for charging the dust.

In the corona process, there must be a source of electrons to initiate and maintain the avalanche process. The electrons are supplied from naturally occurring ionizing radiation, photoionization due to the presence of the corona glow, and, in the case of high temperature operations, from thermal ionization at the electrode surface. For negative corona, electrons are also provided by secondary emission from the impacts between the positive ions and the discharge electrode. Cosmic and terrestrial radiation provide approximately 20 ion-electron pairs per cubic centimeter of gas per second.

Mobilities of the various charge carriers play an important role in the corona generation process. Electron mobility in high fields is approximately 400 times that for ions. In the negative corona case, the electron mobility is such that sparking would occur when the field required to initiate corona is reached unless the electrons are attached to gas molecules to form a stabilizing space charge.

In most industrial gas cleaning applications, there are sufficient quantities of electronegative gases, such as oxygen, so that practically all of the electrons are attached to gas molecules. Gases such as nitrogen, helium, argon, etc., do not form negative ions, and hence a stable negative corona is not possible in these gases.

In positive corona, the electrons generated by the avalanche process flow toward the collection electrode. Since the positive ions are the charge carriers, they serve to provide an effective space charge, and the presence of an electronegative gas is not required for positive corona. Sources of electrons for initiating and maintaining avalanche in a positive corona are cosmic radiation and photoionization due to the corona glow.

Positive and negative corona differ in several important aspects. In appearance, the positive corona is a rather uniform sheath surrounding the discharge electrode. In contrast, negative corona appears as localized discharges from points on a clean wire and as localized tufts along the dust-coated electrode. The voltage-current characteristics of the negative corona are superior to those of positive corona at the temperature at which most precipitators operate. Higher operating voltages and currents can be reached prior to disruptive sparking. It is postulated that a spark or arc breakdown in the interelectrode space occurs by formation of a streamer originating at the positive electrode surface. In the positive corona, the origin of the streamer would be at the surface of the discharge wire, and hence in a high field region. In the negative corona, the positive electrode is the collection plate and the field near this surface is considerably less than at the discharge electrode; hence a higher voltage would be required for spark propagation.

Negative corona is accompanied by the generation of ozone, and therefore is usually not used for cleaning air in inhabited space. However, most industrial gas cleaning precipitators utilize negative corona because of its inherently superior electrical characteristics which lead to increased efficiency at the temperatures at which they are used.

Geometry of the electrodes, gas composition, and gas conditions have important influences on corona generation. The diameter of the discharge wire and the electrode spacing determine the voltage gradient, and hence the variation in electric field strength. The electric field varies as the reciprocal of the radius near a small diameter wire. Hence, with a very small wire, the electric field near the surface can be quite high, often in the range of 50-100 kV/cm. The avalanche process requires the presence of a high electric field over a given distance. In general, the smaller diameter wire requires a higher electric field strength for initiation of corona. For a given spacing, however, the onset of corona occurs at a lower voltage for the smaller diameter wire. Also, for a given voltage, higher currents are obtained with smaller diameter discharge electrodes.

Temperature and pressure influence the generation of corona by changing the gas density. In the avalanche process, the time available for accelerating an electron between collisions is a function of gas density. With increased molecular spacing, higher velocities can be achieved between collisions. Thus, ionizing energy can be achieved with low electric fields for low gas densities.

A second effect, in the case of the negative corona, is that the increased molecular spacing results in the penetration of free electrons further into the interelectrode region before capture to form a negative ion. This results in an increased average mobility in the interelectrode space, and hence a higher current. Additionally, at very high temperatures (above about 1500°F) thermionic emission increases, further increasing the number of free electrons and the effective average charge mobility. These effects reduce the voltage required for sparkover, so that at high temperatures, positive corona would perhaps give superior voltage-current relationships and improved collection efficiency since electrons move toward the discharge electrode in positive corona.

Corona generation studies of a basic nature are most often made with clean electrodes under laboratory conditions. These conditions are highly idealized in comparison to industrial precipitators. In practical precipitators, the presence of a dust laden gas has several effects on corona generation. First, the dust entering the interelectrode space becomes charged by attachment of negative or positive ions. Because of the much lower mobility of the charged dust, it constitutes a significant space charge. The magnitude of the space charge depends upon the size and quantity of the dust and the magnitude of its charge. The effect of the space charge is to reduce the electric field in the vicinity of the corona glow region and thus it tends to quench the corona and reduce the current. This effect is particularly significant at the inlet section of a precipitator where dust concentrations are highest. Special electrode shapes are often used to minimize this space charge problem at the inlet section.

A second important consideration of the effects of dust on corona generation is the deposits formed on both collection and discharge electrodes. On the collection electrode, dust deposits alter the electric field and sparking conditions as a result of the voltage drop within the dust layer. This effect limits the voltage and current at which the precipitator can operate, and is its chief influence on corona generation.

Dust deposits also form on the discharge electrode in operating precipitators. This deposit can be quite heavy in the case of some types of dust. The effect on corona can be considerable depending on the nature of the deposit and the electrical properties of the dust. If the dust resistivity is reasonably low, the effect of the deposit will be to effectively increase the diameter of the discharge wire. This results in higher voltage required for corona initiation or reduced corona current for a given voltage. If the dust deposit is uneven, an uneven distribution of corona along the length of the wire may result.

If the dust resistivity is high, the effect generally would be to reduce corona current for a given voltage. However, if the deposit is somewhat porous, breakdown of the gas in the interstitial region can occur and the effect of the deposit may be reduced.

The current in a precipitator is carried by free electrons, ions, and charged dust particles. The magnitude of the current carried by each of these is related to the number densities of the carrier, the mobility of the carrier, and the electric field. Mobilities are related to the various physical parameters of the charged particle, but primarily to the charge-to-mass ratio of the carrier. Electrons, with their low mass, have the highest mobility of all the current carriers ($\mu_e \sim 750$ cm^2/volts sec). Oxygen ions would have a lower mobility, about 1/400 that of an electron ($\mu_{O_2} \sim 1.9$ cm^2/volts sec), and charged dust particles would have the lowest mobility of all the current carriers (in the range of 0.02 cm^2/volts sec). These mobilities are for conditions normally encountered in commerical installations. It is thus apparent that for a given electric field, the current carried by each of the carriers is in proportion to their mobilities for the same number densities. For a negative corona, the number densities of the charged particles change in traversing the glow region from the discharge electrode surface. At the surface, the positive ion density is greatest, since all of the positive ions from the avalanche process flow to the discharge electrode. At the boundary of the corona glow region, ion generation ceases; hence the concentration of positive ions is zero beyond that point.

The number of free electrons at the wire surface is minimal and increases, because of the avalanche process, to a maximum at the boundary of the corona glow region. Moving into the quiescent zone, free electrons are captured by the electronegative gas molecules. The probability of electron capture is high due to the number of gas molecules present, so that the electron density rapidly decreases beyond the corona glow boundary.

As the electrons from the corona are captured by the gas molecules to form negative ions, the negative ion concentration increases. Traversing further into the interelectrode space, the negative ions attach to the dust particles present to form charged particles. The number of free ions present then decreases as they are consumed in the particle charging process. A considerable fraction of the negative ions present go to charging the dust particles, although due to the difference in mobilities, the percentage of the current due to bound ions is small.

The currents carried by these various carriers can be determined by their number densities, mobilities, and the electric field strength. It should be remembered, however, that the number densities of the various carriers, as well as current, are important in analysis of precipitator operation.

Particle charging. There are two physical mechanisms by which gas ions impart charge to dust particles in the precipitator. Particles in an electric field cause localized distortion of the field so that electric field lines intersect the particles. Ions present in the field tend to travel in the direction of maximum voltage gradient, which is along electric field lines.

Thus, ions will be intercepted by the dust particles, resulting in a net charge flow to the particle. The ion will be held to the dust particle by an induced image charge force between the ion and dust particle. As additional ions collide with and are held to the particle, it becomes charged to a value sufficient to divert the electric field lines such that they do not intercept the particle. Under this condition, no ions contact the dust particle and it receives no further charge. The electrostatic theory of the process shows that the saturation value of the charge on the particle is related to the magnitude of the electric field in the region where charging takes place, the size of the particle, and the dielectric constant of the particle. The saturation charge is proportional to the square of the particle diameter, thus larger particles are more easily collected than small ones. This mechanism of charging is called field-dependent charging.

The time required for a particle to acquire a saturation charge is an important factor that is often neglected in precipitation theory. Field dependent charging may be described by an asymptotic final value function, and is dependent upon ion density and mobility. If a single particle is introduced into a high ion density field, charging takes place in milliseconds. However, charging times by the field-dependent regime can be appreciable under practical conditions of large dust loading and low currents.

For small particles (diameter $< 0.2\mu$), the field-dependent charging mechanism is less important, and collision between the particles and gas ions is governed primarily by thermal motion of the ion. Equations describing the rate of charging can be derived assuming that charging rate is independent of the magnitude of the electric field. Since ion movement is so greatly influenced by the electric field, the assumption obviously generates considerable error. However, the factors influencing charging rate can be seen under this assumption to be particle diameter, free ion density, and thermal velocity of the ions.

Since the range of thermal velocities has no upper boundary, there is no saturation value associated with diffusion charging. However, as the charge on a particle increases, the probability of impact decreases, so that there is a decreasing charging rate associated with an increasing particle charge. This second charging process is called diffusion charging.

Recent work in the area of diffusion charging has been directed toward obtaining better agreement between experimentally determined values of diffusion charging and those predicted by theory. Studies of the influence of electric field have been made on the basis of approximate solutions to the equations that include the effect of the electric field.

In practical precipitators, field-dependent charging is usually of most interest, but in some applications particles are present in the range where diffusion charging is the predominant mode (< 0.2μ diameter) as well as the area in which both mechanisms are significant. Unified charging equations have been developed covering the size range where both charging regimes are important, and results agree reasonably well with experimental laboratory values.

Particle charging theory indicates several important factors governing precipitator performance. Since the magnitude of the particle charge is dependent upon the magnitude of the electric field in the field-dependent mode, it is important that field strength be kept as high as practical in the region where charging takes place.

A second factor of importance is the rate of charging of the particles. Practical precipitators generally introduce heavy concentrations of uncharged dust in the inlet section of the precipitator. Calculations show that the number of ions required to charge this dust to its saturation value may be large, hence the number of free ions present may be substantially reduced and charging times are not insignificant.

The waveform of the applied voltage is significant, as it influences the peak value of the electric field and the charging time. The saturation value of the particle charge is determined by the peak value of the electric field. However, charging only occurs during the interval of time that the applied field exceeds the self-field corresponding to the charge on the particle. Consequently, longer times will be required to reach saturation for a varying voltage than for a pure d-c voltage. However, the varying voltage is preferable for spark quenching and permits operation at a higher average voltage.

The electric field in a precipitator determines the maximum value of the particle charge due to field-dependent charging and also the force acting on a charged particle. Since the electrical field enters the collection efficiency equations effectively as a squared term, it is important that the magnitude of the field be maintained as high as practical.

The electric field strength is determined by the electrostatic component, which is related to the precipitator geometry and the applied voltage; and by the space charge component, which is related to the presence of charged particles (ions and charged particulate) in the interelectrode space. The design of the precipitator can be varied to alter the geometry of the discharge electrode and the electrode spacing. These factors can determine the magnitude of the electrostatic component. Variations in electrode geometry can also alter the corona current, which in turn influences the electric field by changing the space charge contribution. Equations describing the electric field for clean electrodes have been developed from classical electrical theory. Utilizing these equations, it is possible to predict the field at any location, assuming clean electrodes.

In a practical precipitator, dust accumulations on the collection electrodes limit the maximum voltage, and hence the electric field strength at which the precipitator can operate. The voltage drop across the dust layer is dependent upon the corona current density, the electrical resistivity of the dust, and the thickness of the dust deposit. For high resistivity dusts, the voltage drop across the collected dust layer can be in the neighborhood of 10-20 kV, assuming reasonable current densities and dust deposit thicknesses. Obviously, the electrical energization equipment must be capable of providing sufficient voltage to accommodate this voltage drop, while maintaining adequate voltage across the interelectrode spaces. The effect of the resistivity of the dust layer, however, is more severe than its influence on power supply voltage. The electric field in the dust layer can be quite high for high resistivity dust. This high field region at the anode surface can lead to sparkover at lower applied voltages, thus limiting the maximum operating voltage of the precipitator.

A second condition associated with high dust resistivity can also influence particle charging and the magnitude of the electric field. Once sparking occurs, a crater is formed in the dust layer, and current densities in the localized area can result in localized electric fields that are sufficiently high to initiate a corona emanating from the base of the crater. This corona results in positive ion production and, due to the direction of the electric field, these ions flow toward the discharge electrode. Collisions with dust particles tend to charge them with opposite polarity to that required for collection. Also, collision with negative ions tends to neutralize them, reducing the ion density in the interelectrode space.

If dust resistivity is further increased, a diffuse corona glow will appear over the large areas of the dust surface. Under these conditions the positive ion production by the reverse corona is sufficient to completely disrupt the charging process, and effective precipitation is not possible under these conditions.

Particle collection. The forces acting on a charged particle in a precipitator are gravitational, inertial, electrical, and aerodynamic. The latter two are the principal ones of importance in electrostatic precipitation.

If a particle is suspended in a laminar gas flow stream in a pipe and wire precipitator, a force due to the electric field and particulate charge will act on the particle in the direction of the collection electrode. This force is opposed by the viscous drag force of the gas. In sufficient time, which is short for small particles, the particle would reach a terminal velocity at which point the electrical and viscous drag forces would be equal. In precipitator terminology, this is called the migration velocity. The other force acting on the particle is the aerodynamic force by the gas stream. The motion of the particle will be along the line defined by the vector sum of these two forces. Under laminar flow, all particles would be collected in a given length of the precipitator and the collection efficiency for shorter lengths would be linearly related to precipitator length.

In practical size precipitators, however, laminar flow is practically never achieved. Consequently, the turbulent gas flow causes particles to follow a random path through the precipitator. The magnitude of the forces due to the turbulent gas flow is large compared to the electrical forces. However, at the boundary layer the gas flow is laminar and particles entering the boundary layer will be collected. The collection efficiency is therefore related to the probability of a particle entering the boundary layer. Studies by Anderson, Deutsch, and White of particle collection in a turbulent gas stream have shown theoretically that collection efficiencies are exponentially related to the collection surface, the gas volume handled, and the migration velocity of a particle. The equation, known generally as the Deutsch-Anderson equation, is of the form $\eta = 1 - \exp\left(-\frac{A}{v_g}w\right)$.

The derivations of the efficiency equation are based on the assumption that there is a reasonably constant distribution of the particles in any cross section of the precipitator due to turbulent mixing of the gas. In addition to this assumption, there are several basic conditions that apply to the derivation of the equation. Utilizing the relation for the theoretical migration velocity $w = \frac{2\epsilon_0 E_0 E_p a}{\eta}$ generally associated with the efficiency equation neglects any contribution of diffusion charging. Also, the calculation is based on a single particle size. The equation also includes no term to account for reentrainment of collected dusts, uneven distribution of the gas flow, or other factors inherent in practical precipitator operation.

A principal practical use of the Deutsch-Anderson equation has been in relating measured collection efficiency to the collecting surface area and gas volume. In such cases, the term w as calculated from the Deutsch-Anderson equation is a parameter, rather than the migration velocity given by theoretical considerations. In this case, it is called effective migration velocity or precipitation rate parameter. The term is useful in describing the effectiveness with which a given dust can be collected, and is widely used in design and analysis of precipitators.

From a theoretical as well as a practical standpoint, the distribution of particles within the precipitator is important. There is some evidence to indicate that particle distribution within the precipitator may not be uniform and that diffusional forces may also play a role in collection efficiency.

Removal. Once collected, the dust or liquid aerosol must be removed from the precipitator. This can be accomplished by flowing a liquid down the collection electrode to wash the collected dust, or by rapping the electrodes to impart an acceleration to dislodge the dust, which falls into a hopper for subsequent removal. Liquid aerosols normally coalesce and drain from the plates so that removal is not a problem.

In dry removal systems, rapping of the collection electrode to remove the dust is normally done on a periodic basis. Successful rapping depends upon accumulation of sufficient thickness of material on the plate so that it falls in large agglomerates into the hopper. There is always some reentrainment of the dust so that effective rapping must minimize the amount of material reentrained in the gas stream.

The accelerations required to remove the collected dust vary with the properties of the dust and gas stream. Forces of cohesion and adhesion consist of molecular (van der Waals), electrical, and mechanical forces. Some dusts adhere tenaciously to the collection surface and require substantial accelerations to dislodge them. Variations in operating temperature, gas composition, or both, can alter the forces required for successful rapping. Electrical forces, which are related to current density and dust resistivity, are also significant in holding the collected material to the plate, and therefore affect the forces required for rapping. Since current densities are higher at the discharge electrode than at the collecting electrode, greater forces are often required to maintain them relatively free of dust deposits than are required at the collection plates.

Reentrainment of the dust during rapping is evidenced by increased dust loadings at the precipitator exit following a rap. To minimize this effect, only small sections of the precipitator are rapped at one time.

Electrical energization. The function of electrical energization is to provide optimum electrical conditions for particle charging and collection. The energization equipment consists of a transformer to step up the voltage from the normal supply line to between 30-100 kV which is required for precipitation. The particular voltage is a function of electrode (wire-to-plate) spacing, and the spacing is generally chosen to minimize the influence of misalignments of the electrodes resulting from faulty construction, warping, etc. A rectifier, usually of the vacuum tube or silicon type, converts the alternating voltage to d-c to give unipolar ions. An automatic control system is usually provided to maintain optimum voltage conditions for precipitation. The control system can operate from spark rate, secondary or primary voltage, or other parameters.

The power capacity of the energization equipment is determined by the precipitator size or quantity of gas flow, design efficiency of the precipitator, and properties of the dust and gas. The manner in which the power is applied varies with the application, and the policies of the equipment manufacturer. The principal variable is the number of independently powered precipitator sections that make up the total power supply. Increasing the number of sections by using a large number of smaller power supplies is advantageous if the precipitator is operating in a spark-limited mode, as a higher voltage can be maintained for a given spark rate. The size of the power supply also determines the internal impedance of the supply, hence large power supplies with high current capacities have low impedances, which are not as effective in spark quenching as the smaller, high impedance supplies. Smaller power supply sections also tend to minimize effects of plate misalignment or other localized disturbances. Finally on large systems, the influence of an outage of a section of the precipitator is not as pronounced in systems comprised of smaller power supply sections where many independent sections are used.

Analysis of the electrical characteristics of a precipitator shows that it consists primarily of a parallel capacitive and resistive load, the value of which is determined by the corona current and voltage and precipitator dimensions. The value of the capacitance is large enough to maintain the voltage at a high level between cycles, even though the power supply is unfiltered. The electrical characteristics of the dust deposit also influence the electrical operation of precipitators. The effect of the filtering characteristics of the dust layer is to smooth out voltage fluctuations so that higher peak voltages can be applied for a given spark rate if the voltage waveform has a high rise rate. On the other hand, charging times may be increased by these voltage waveform alterations, hence for the optimum design, both effects must be considered.

Systems analysis. Despite its seeming simplicity, the interaction of the variables makes it difficult to analyze the performance of a precipitator without considering the system as a whole. The systems analysis approach permits a review of the various parameters controlling system performance and permits a rational basis for precipitator design and analysis.

A simplified systems analysis has been developed which relates most of the important variables and permits a computerized method of precipitator analysis or performance evaluation.

The systems model is programmed to determine the collection efficiency for each discrete particle size range for each increment of length of the precipitator by calculating the following: the field strength as a function of radius at each increment of distance through the precipitator, the saturation charge on the dust, the actual charge on the dust at each increment from considerations of the free ion densities, and the amount of material in each size range that is removed at each increment. From this, the total collection efficiency can be calculated.

Comparisons of efficiencies predicted from the systems model with those measured in field tests show good agreement, except where unusual conditions, such as excessive reentrainment, were suspected.

The general philosophy behind the systems model is that it permits a satisfactory calculation of performance based on known theory, whereas theoretical calculations based on very elementary or simplified theory do not. Refinement of the model to include such factors as reentrainment, voltage-current characteristics, sparkover effects, spatial distribution of the dust, diffusion charging, and gas distribution, should permit a more theoretically correct analysis and should give better agreement between measured and calculated performance.

Design. The design of precipitators involves the determination of precipitator size and electrical energization equipment required to give a desired efficiency, the design of a gas flow system to provide acceptable gas flow quality, structural design of the precipitator shell and supports, selection of the rapping equipment, and selection of the electrode configuration.

Present design methodology is generally based upon empirical relations, the values of which have been obtained from experience with similar applications. There are several approaches to the selection of the precipitator size. In general, these methods involve the selection of a precipitation rate parameter and determination of the collection plate area required from the Deutsch-Anderson equation or from design curves based upon field experience. The precipitation rate parameter varies for different applications and often varies considerably within the same application area due to variations in gas and dust properties.

Selection of the precipitation rate parameter can be made on the basis of experience with similar installations or from experimentally derived curves relating precipitation rate parameters to dust properties. For many applications, the range of precipitation rate parameter variations is small (of the order of ±10%). In such cases, the uncertainty in plate area requirements is of the same magnitude. In other instances, variations can be as high as 400-500%, so that some method for reducing the uncertainty is highly desirable. In general, some property of the effluent from the industrial process has been related to precipitation rate parameter and an empirical relationship is derived to predict the value of the precipitation rate parameter. In the case of fly ash precipitators, sulfur content of the coal and resistivity of the dust are commonly used to establish this value. Particle size distribution is another significant variable, and curves relating precipitation rate parameter with any other variable should be modified to compensate for particle size variations if sufficient data are available.

Power requirements for a precipitator vary with collection efficiency. Selection of the power requirements is generally based on curves relating efficiency with corona power per unit volume of gas flow (watts/cfm). These curves are experimentally developed for each type of application and vary with dust properties. These curves are usually based on total delivered secondary power, and power supply capacity is selected on the basis of a power supply efficiency (from 60-75%) and the standard power supply size that will meet the efficiency requirements.

Sectionalization is also based on empirical information derived from experience. These curves must be consistent with those based on power requirements and on relationships involving collection surface area, since the same efficiencies can be achieved through the use of fewer sections and greater collection area for installations operating in a spark rate limited mode.

Design of the gas flow system is generally based on model studies with large systems, and its importance to good precipitation cannot be overemphasized.

Selection of the number of rappers, type of electrodes, etc., varies among manufacturers and with the type of dust being collected. Structural design is relatively straightforward.

One of the principal difficulties encountered by the users of electrostatic precipitators is the evaluation of bids for specific installations. Although precipitator bids are based on guaranteed performance, there are many examples of precipitator installations that fail to meet design performance by a wide margin. It is not uncommon for bids to vary considerably in the collection surface area, the amount of power and degree of electrical sectionalization, and the type of gas flow distribution systems. The user is therefore faced with the problem of evaluating the adequacy of each design for meeting his requirements. The ability to interpret bids requires experience with the particular type of dust or a method of assessing the effect of the design variations on performance.

A technique for evaluating design parameters for given dust and gas conditions has been developed based on the method of regression analysis. Based on a group of approximately 75 tests on 20 installations, equations predicting the precipitation rate parameter as functions of gas and fuel properties have been developed. An overall correlation coefficient of about 0.85 has been obtained, with maximum uncertainties of about 25% in the precipitation rate parameter for fly ash precipitators. This is rather good agreement since design and performance parameters may vary considerably more than for fly ash collection.

Mechanical components. The two general types of precipitators currently used are the tubular and plate types. The tubular precipitator consists of cylindrical collection electrodes with discharge electrodes located on the axis of the cylinder. Gas to be cleaned passes through the annular space between electrodes and the dust is collected on the outer cylinder. This type construction is used in wet electrode systems, in high-pressure, high-temperature applications, in some types of precipitators collecting liquid aerosol particles, and for small dry collection installations.

The plate type precipitator consists of parallel collecting plates with discharge electrodes located between the plates. Collecting electrode plates are usually 12 to 40 feet high and spaced 6 to 12 inches apart. The length of the ducts in the direction of gas travel can vary according to the precipitator design. Total length can be from around 12 to 24 feet or longer for very large installations.

Mechanical components which make up a precipitator are the shell, electrodes, hoppers, rappers, support members, and the necessary electrical feedthrough and support backings.

The shell can be rectangular or cylindrical and can be constructed of steel, tile or concrete. Thermal insulation is usually provided in the case of corrosive gases to maintain the shell above the dew point temperature to minimize corrosion. Design of the shell generally follows straightforward structural engineering practice.

The shell and electrode configurations can be arranged to divide the gas flow and to provide independent sections that can be separately energized. When parallel gas flow paths are provided, each path is referred to as a duct or chamber.

Discharge electrodes in both cylindrical and plate type precipitators are of a variety of types depending upon the application and the precipitator manufacturer. The discharge electrodes can be small diameter (~0.1 inch) wire, square wire, or fabricated structures of various types. The primary consideration in discharge electrode selection is to obtain desirable voltage-current characteristics and to provide mechanical strength for resistance to corrosion and fatigue. In general, American practice is to utilize electrode structures supported at the top, with weights at the hopper end to maintain the electrode taut. Guides are provided to maintain alignment. European practice is generally to use a mast or frame for rigid support of the discharge electrodes. Various discharge electrode configurations can be used with either type of mounting.

Collecting electrodes in plate type precipitators are generally flat plates with various types of stiffeners and baffles. The baffles provide shielding of the collected dust to reduce reentrainment during rapping and to reduce scouring of the plates due to gas flow.

Single impact or vibrational rappers are provided for dust removal in dry type precipitators. Rappers can be electromagnetically, pneumatically, or mechanically actuated. The major requirement for successful rapping is to deliver sufficient impact to the electrodes to dislodge the dust without causing excessive reentrainment. The acceleration required to remove the dust varies with the type of dust and gas composition. Rapping is generally specified in terms of the energy delivered per rap and the number of rappers per square foot for the collecting surface or per length of wire for the discharge electrode.

Dust removal can be through flat bottom pans with scrapers to move the collected material to a screen conveyor or through pyramidal hoppers where it is removed by conveyors or vacuum systems. The latter type is the most prevalent.

Gas flow. Gas flow in practical precipitators is well within the turbulent region. When exiting from the process, gas velocity usually is relatively high and often uneven. Gas velocity must be reduced to a relatively low level and turbulence controlled before entering the precipitator for good precipitation. Poor quality gas flow can affect precipitator performance by scouring the plates in localized regions of high gas velocity and by reducing performance due to the exponential relationship between efficiency and gas volume flow.

Often, space limitations preclude more conventional methods of achieving uniform gas flow, and turning vanes, splitters, straighteners, and diffusion plates must be designed to provide adequate gas flow quality. The Industrial Gas Cleaning Institute recommends a minimum gas flow quality such that 85% of local velocities is within 25% of the mean, with no reading more than ±40% from the mean.

Because of the difficulties in predicting gas flow quality, the use of physical models is almost universal. Models are usually constructed of pressed hardwood or acrylic plastic. Smoke streamer patterns and pitot tube traverses are used to indicate gas flow uniformity. Models have been historically constructed $\frac{1}{4}$ to $\frac{3}{8}$ size with the Reynolds number held constant. However, with the trend toward larger plants, models constructed to $\frac{1}{16}$ scale have been used. The use of smaller scale models tends to give less accurate results.

Resistivity. Electrical resistivity of the dust is an important factor in the performance of electrostatic precipitators. If the resistivity of the collected dust is higher than about 2×10^{10} ohm-cm, excessive sparking or reverse corona can occur, thereby limiting precipitator performance.

Two distinct types of electrical conduction occur. One type is conduction by free electrons within the particles. This type of conduction depends upon the electron activation energy (a material property) and temperature. Many industrial dusts are composed of metallic oxides, sulfates, etc., which have low activation energies so that the electrical conductivity is low at temperatures in the range of 300-400°F. At higher temperatures, however, conductivity becomes greater and for most dusts this is the primary conduction mechanism at temperatures above 450-500°F.

The second kind of conduction is conduction over the particle surfaces owing to adsorption of moisture or certain chemicals such as sulfuric acid. Adsorption increases with decreasing temperature and hence particle conductivity also increases with decreasing temperature. Moisture is often referred to as the primary conditioning agent and other chemical adsorbates as secondary conditioning agents.

The role of the secondary conditioning agents is not clearly understood in all cases. It is postulated that the secondary conditioning agent may alter the surface of the dust, thus enhancing the rate of moisture adsorption and hence the conductivity. The effectiveness of the secondary conditioning agent varies with the type of dust. There is evidence that an acid conditioning agent, such as SO_3, is more effective in conditioning a basic dust, whereas a basic conditioning agent, such as NH_3, is more effective in conditioning an acidic dust. There is some evidence that the conditioning agent and moisture adsorb or condense onto the dust surface together to form the conductive layer and subsequently may react with the dust layer to alter the resistivity. Effects of additions of limestone to particulate emission from sources such as power generator boilers and sinter machines tend to indicate that reactions between dust and conditioning agent may detrimentally influence electrical conductivity.

In some instances of high resistivity dust, additions of a conditioning agent to the effluent gas have resulted in substantial reductions in resistivity and enhanced collection. Examples are SO_3 additions to the gas from power generator boilers and ammonia additions to gas from catalytic cracking units used in petroleum refining. However, additions of relatively large quantities of chemical additives have failed to improve performance in some applications. But since secondary conditioning agents are known to be highly specific and selective in effectiveness, there is no appropriate reason for expecting random additives to work. Causes for this condition are not fully understood.

Measurement of performance. Measurement of precipitator performance generally includes dust loadings at the precipitator inlet and outlet, gas velocity distribution, electrical current and voltage input to the precipitator, and gas composition. Dust resistivity is an important parameter that should be measured, but often is not.

Dust loadings are normally measured by a sampling probe and a dust collector, such as a thimble. Prior to sampling, a gas velocity distribution traverse is made so that dust samples can be taken isokinetically to minimize selective size collection. Sources of error in sampling are usually attributed to anisokinetic sampling, improper probe handling, dust collection on the walls of the sampling train or dust collector, and errors in gas flow measurement. Sampling procedures require careful attention to detail and the development of skills in the sampling procedures.

Resistivity of the dust sample must be made in-situ to be meaningful. Laboratory measurements may be high by orders of magnitude and often fail to correlate with in-situ values.

In-situ resistivity can be measured by determining the current flow through a given volume of collected dust when a known voltage is impressed across it. Several types of resistivity probes can be used for this purpose. In some types, the dust is deposited electrostatically utilizing a point-plane precipitator. Other type probes utilize a cyclone type mechanical collector. The errors involved include those associated with obtaining a representative sample. Particle size and degree of packing can influence the apparent resistivity of the dust layer.

Troubleshooting and maintenance. Causes for a precipitator to fail to achieve its design efficiency can be due to inadequate design, electrical difficulties, improper gas flow, inadequate rapping, installation problems, electrode misalignment, poor maintenance, or improper operation.

Indications of electrical difficulties can usually be observed from the levels of corona power input. Efficiency is generally related to power input, and if inadequate power densities are indicated, difficulties can usually be traced to dust resistivity, unusually fine particle size, electrode misalignment, improper control operation, or dust accumulation on the electrodes. Improper gas flow can be determined by measurement of the gas flow distribution. Poor gas flow can result from improper design, plugging of distribution plates, build-up of dust on dust walls and turning vanes, etc.

Improper rapping is usually manifested in excessive dust deposits on the collection and discharge electrodes. Adequacy of rapping can be measured by accelerometers mounted on the electrodes. Accelerations required to dislodge the dust vary with type of dust and operating conditions, and rapping must be adjusted to maintain the desired thickness of the dust deposit without excessive reentrainment. Visual observation of the interior of the outlet flue from the precipitator is often a sensitive and revealing method for checking rapper operation.

Maintenance schedules should be set up for inspection, servicing, and repair of critical components. These components include rappers, feed-through bushings, transformers, electrodes, ash removal equipment, and electrical controls. Excessive dust deposits, corrosion, broken wires, etc. are common types of difficulties encountered.

Electrostatic augmentation and unusual designs. Electrostatic augmentation of fabric filters, packed bed filters, and wet scrubbers has been studied in some detail. Performance of fabric filters varies with the type of dust deposit and the thickness of the deposit. Pressure drop is also generally related to the dust deposit. The filtering action is generally considered to occur by the trapping of dust on the collected layer. If a single particle is too large to pass through an interstitial region, it is trapped on the dust layer and separated from the gas stream.

Electrostatic augmentation involves establishing an electric field between the fabric and another electrode, precharging the dust particle, or both. The effect of electrostatic augmentation is that the interstitial openings in the fabric material function as if they were smaller and hence smaller particles are retained. Its principal advantage has been in the more rapid build-up of the dust layer and somewhat higher efficiency for a given pressure drop.

Loose bed filters are notably inefficient in collection of small particles. However, if charged particles are introduced or if an electrostatic field is impressed across the filter, or both, the dust particles will deposit on the filter bed. The effect is to provide increased collection surface area in a two stage precipitator. Greatly increased efficiency can be achieved over that for a conventional loose bed filter. The potential for increased collection surface would indicate the possibility of enhanced collection over a two stage precipitator with the same metallic plate area. The obvious disadvantage is in removal of the collected dust, which would require liquid backwash or circulation and cleaning of the filter material.

Augmentation of wet scrubbers is intended to provide better contact between the particulate and the scrubbing liquid by utilization of the attractive force between the charged particles. The attractive force between a charged dust particle and an oppositely charged liquid droplet varies with the distance of separation. Thus, with separation distances of 10μ, the attractive force is approximately equal to the gravitational force.

The use of the space charge, developed as a result of the dust charge or as a result of other charged material, has often been the basis of a precipitator concept in which no high voltage is applied to the collection plate.

Fields developed as a result of space charge can be quite high provided the concentration of charged dust is high and there is ample spacing between electrodes. However, as dust is collected, the space charge decreases and collection efficiency decreases. Charged water drops have also been utilized to maintain a higher space charge field. These approaches are more suited to specialized applications and their practicality for industrial gas cleaning has not been demonstrated.

Application of Electrostatic Precipitators in Industrial Dust Control

The principal use of electrostatic precipitators in the control of industrial dusts has been in the following major areas.

1. Electric Power Generation
2. Pulp and Paper
3. Rock Products
4. Iron and Steel
5. Nonferrous Metals
6. Petroleum
7. Chemical Industry
8. Municipal Incinerators
9. Miscellaneous Applications

The use of electrostatic precipitators was reviewed in these areas to determine the extent of the use of precipitators in each area, the range of input variables, and the design factors, costs, and problems peculiar to the use of precipitators in the particular industry. The approach followed in this study was to: (1) review the process to determine the dust and gas compositions and properties, (2) determine from the users the extent to which design, test, and cost data were available, and (3) integrate the data supplied by Research-Cottrell into an application area report. The reports from the various industries are compiled into a single volume covering the major areas of application.

The results of the survey are tabulated in Table 2 by industry.

Cement

In the cement industry, a total of nine companies were contacted. Of these, five were visited and made data available to the survey.

Pulp and Paper

Data from the pulp and paper industry were supplied by Rust Engineering Co. Much of the data were taken directly from bids on installations for which Rust was the engineering contractor. In addition to this source of data, test results were obtained from nine installations. The test data were obtained from the mills as a result of personal visits and telephone contacts.

Magnesia

Data were supplied for all three magnesia plants contacted. Two of these were visited and the third furnished the data requested.

Table 2

A Survey of the Use of Electrostatic Precipitators in Various Industries

	Total Contacted	Number Furnishing Data	Installations on Which Data Rec'd
Cement	9	5	5
Pulp and Paper	19	19	19
Magnesia	3	3	3
Phosphorus	5	3	3
Lime	5	4	4
Gypsum	4	1	1
Petroleum	3	0	0
Iron and Steel	11	7	28
Electric Power Generation	5	5	53
Nonferrous Metals	2	0	0
Municipal Incinerators	1	1	2

Phosphorus

Five producers of phosphorus were contacted. Three plants were visited and furnished data.

Lime

Five companies with electrostatic precipitators installed on lime kilns were contacted, one was visited and furnished data. Three companies furnished the data requested on the survey form.

Gypsum

Several companies were contacted, one furnished data and one had no data in their files.

Sulfuric Acid

Several companies were contacted and one furnished data.

Petroleum

Three companies were contacted. All wanted to work through the American Petroleum Institute Committee. The request submitted to the committee was not honored.

Iron and Steel

Eleven companies were contacted for data covering the iron and steel applications. Of these, seven companies supplied data on at least some applications. Of those furnishing data, information was supplied on one precipitator for an iron cupola, four sinter machines, five open hearth furnaces, 15 blast furnaces, 11 by-product coke ovens, and three BOF furnaces.

Electric Power Generation

Data were requested from five electric utility companies and were received on 53 precipitators from all five utilities.

Nonferrous Metals

Data were requested from two companies, but no user data were obtained.

Incinerators

One installation was visited and limited data obtained since the bid data were incomplete and no test data were available.

Data Sources

In addition to the data received from the survey, published literature provided data on some specific installations in sufficient detail for use.

The data supplied from the various sources consisted of design and test data. Design data were generally more readily available since many installations had not been tested. Where tests have been conducted, the primary goal has been to determine stack emissions and electrical data were often not recorded.

Table 3 is a summary of the precipitator applications by year showing the total number of precipitators installed in each area. These data are based on records supplied by Research-Cottrell and represent "lost jobs" as well as those furnished by Research-Cottrell. The following is a descriptive summary of the section of the manual covering applications of precipitators in various industries.

Descriptive Summary of Application of Electrostatic Precipitators in Major Application Areas

Part II of the manual on electrostatic precipitators is a review of the application of electrostatic precipitators in each of eight major application areas. In addition, an analysis is presented of the use of dust control equipment in a number of manufacturing operations and the factors influencing the use of electrostatic precipitators in new dust control applications.

Within each application area, a review of the process is given with particular emphasis on the dust and gaseous emissions. This is followed by a tabulation of input and design parameters for precipitators operating on various types of dust control problems and an analysis of critical design parameters and test results. Cost data are also presented to show the range of FOB and erected precipitator costs for various efficiency levels and gas volumes.

The information presented has been derived from a review of the literature pertaining to the particular application, a tabulation of information by Research-Cottrell, Inc., of design, cost, and input parameter data, and, finally, an analysis of design and test data obtained from a survey of operating installations. The following is a summary of the information presented in greater detail in the following chapters of the manual.

Electric power generation. Electrostatic precipitators are used in the electric power generation industry principally for the control of emissions from coal-fired steam generating plants. Although there is a trend toward the use of nuclear power generation, the expected increase in the total power consumption and the upgrading of existing control equipment is expected to result in the expanded use of electrostatic precipitators in this application for a number of years.

Fly ash is generated from both pulverized-coal-fired boilers and cyclone boilers. The character and amount of fly ash from these two types of boilers vary with the type and chemistry of the coal being burned and the particular operating conditions of the boiler. The ash content of the coals being burned varies from 5-25%, and, together with the ash-fusion temperature and boiler operation, determines the dust load that must be handled. Typical dust loads range from 2-7 gr/cu ft of gas.

The particle size distribution of fly ash varies with the type of boiler and type of coal. For a pulverized fuel boiler, the mass median diameter of the fly ash is around 10-15 microns. For a cyclone furnace, the mass median diameter varies over a wider range and is generally smaller (5-15 microns). It is rather common practice to precede fly ash precipitators with mechanical collectors which remove mainly the large size fraction of the dust. The mass median diameter of the fly ash to a precipitator preceded by a mechanical collector is around 3 microns.

The resistivity of the collected fly ash is perhaps the most important property influencing collection by electrostatic precipitators. If the resistivity is high (above about 2×10^{10} ohm-cm), the voltage and current to the precipitator must be kept low to prevent excessive sparking and back corona. Under these conditions, the charge acquired by the dust will be low, the charging time will be long, and the collection field will be low. Consequently, the performance of the precipitator will be impaired.

At the other extreme, too low a resistivity will permit reentrainment of the collected dust and result in low efficiency. There is an optimum resistivity therefore for maximum precipitator performance.

Resistivity of fly ash is determined by the temperature of the flue gas and the chemistry of the coal. At temperatures of around 450-500°F or above, volume conductivity predominates and the resistivity is always below the critical 2×10^{10}. As the temperature decreases, resistivity increases. This trend would continue under bone-dry conditions. However, at temperatures in the range of 300°F, moisture in the flue gas is adsorbed on the fly ash surface and alters its resistivity by a mechanism called surface conduction. The lower the temperature, the greater the rate of adsorption, so that resistivity continues to decrease with decreasing temperatures.

In addition to temperature, the percentage of sulfur in the coal also influences fly ash resistivity. Studies of fly ash resistivity indicate that the SO_3 present in the flue gas acts to alter the rate of moisture adsorption and serves as a secondary conditioning agent. On the average, the amount of SO_3 present in the flue gas is directly related to the sulfur content of the coal. However, operating conditions in the boiler, and perhaps other constituents of the fly ash, govern the quantity of sulfur appearing as SO_3.

In addition to the temperature and the amount of SO_3 present in the gas, the chemistry of the fly ash appears to influence the adsorption rate. A basic ash is reported to contribute to a higher rate of adsorption of SO_3. Thus, even though there is a good statistical correlation between sulfur content of the coal and fly ash resistivity, the variations for a single condition are too great to permit accurate prediction of resistivity based on sulfur content alone.

Measurement of resistivity of fly ash should be made in-situ, utilizing the techniques described in Chapter 12 of Part I of the manual.

Fly ash precipitators are generally designed on the basis of the Deutsch-Anderson equation relating efficiency to gas volume and collecting surface area. Experience with large numbers of precipitators has shown, however, that the precipitation rate parameters can vary between around 3 cm/sec to 17 cm/sec. The major problem in the design, therefore, is to narrow the range of uncertainty in selection of the precipitation rate parameter.

The value of the precipitation rate parameter for most fly ash precipitators is around 10 cm/sec (0.33 ft/sec). Variations from this value can occur if the fly ash properties are either more favorable or more adverse than normal.

Low values of precipitation rate parameter are normally associated with excessive gas velocities, uneven gas flow distribution, high dust resistivity, low dust resistivity, or improper rapping. Problems of gas flow distribution and gas velocity can be handled by proper design through the use of models, etc. These problems are perhaps made more severe in the case of fly ash precipitators by the large gas volumes that must be handled.

High resistivity problems are usually associated with high ash, low sulfur coals. Low resistivity problems can occur if the gas temperature is low and high sulfur coal is being burned.

Problems with high fly ash resistivity can be resolved by several approaches which include: (1) increasing precipitator size, (2) changing the flue gas temperature, or (3) adding chemical conditioning agents.

The first of these alternatives is straightforward; however, about three times the normal collection surface area may be required and the costs of this alternative may be prohibitive.

Precipitators are normally located downstream of the air heater and operate at temperatures in the range of 250-350°F. However, they can be located ahead of the air heater where gas temperatures are in the vicinity of 700°F. At these temperatures, the dust resistivity is determined principally by volume conductivity and is independent of the sulfur content of the coal. Since gas volumes are about 1.5 times those at 300°F, additional precipitator capacity is required. However, this alternative may be attractive for many applications.

Operation of precipitators following the air heater can utilize the option of lowering the flue gas temperature to reduce dust resistivity. Reduction of temperatures from 300°F to 260-270°F can reduce fly ash resistivities by factors of 10 or more, and can minimize the high resistivity problem. Because resistivities can change so rapidly within this temperature range, control may become a problem.

Use of chemical additives to control dust resistivity is a third alternative. Small additions of SO_3 (up to 10-15 ppm) to the flue gas have altered dust resistivity by factors of 10 or more and resulted in substantial improvements on precipitators which are limited by sparking due to high dust resistivity. Other chemical additives, such as H_2SO_4, are being evaluated as conditioning agents.

Problems with low dust resistivity have been encountered when burning high sulfur coal and operating at low flue gas temperatures. The difficulty has been identified as excessive scouring or reentrainment due to the reduction in force holding the dust to the collection plate. The problem is associated with high gas velocity and is apparent when relationships between gas velocity and precipitation rate parameter are plotted for various resistivities. This problem can be resolved by increasing the flue gas temperature, injection of ammonia, reduction in gas velocity, or a combination of these effects.

In addition to determining the collection surface area, design of a fly ash precipitator also includes determining the power supply requirements. It has been shown empirically that efficiency is related to the corona power delivered to the precipitator. Curves showing this relationship for fly ash precipitators show a good correlation and are useful in both design and troubleshooting of fly ash precipitators.

The number of independently energized bus sections is another design variable. Since fly ash precipitators are generally designed to handle large gas volumes, the degree of sectionalization is of greater importance than in some other applications. If very high collection efficiencies are desired, a higher degree of sectionalization should be used. The advantages are: (1) higher operating voltages in the spark-limited mode, (2) lower internal impedance with better spark quenching, and (3) less percentage of the precipitator would be disabled by the outage of a single section.

Since a number of factors influence precipitator performance, and since these vary between installations, a technique of regression analysis has been developed by several investigators exploring precipitator operation. A method relating the expected precipitation rate parameter with the significant parameters has been developed to serve as a guide to analysis of precipitator specifications. The technique gives a correlation coefficient of about 0.85. A second regression analysis performed on data from a group of installations gave a correlation coefficient of around 0.9 when using more fundamental precipitator and dust parameters.

Pulp and paper. Electrostatic precipitators are used in the pulp and paper industry to remove particulates carried by the effluent gases from black liquor recovery boilers.

The kraft or sulfate process constitutes approximately 55% of the total production in this country. Of these kraft mills, about 65% have electrostatic precipitators installed on the recovery boiler.

The economics of the kraft process requires the recovery and reuse of the spent chemicals used in the cooking process and recovery of the heat content of the concentrated spent liquor. This is accomplished by combustion in the recovery boiler which releases large volumes of flue gases. During combustion, a significant fraction of the recoverable chemicals is entrained as particulates with the flue gas. Recovery of these particulates constitutes a significant economic factor as well as a means for controlling air pollution.

Particulate emissions from the recovery boiler are extremely fine hygroscopic particles, composed principally of sodium sulfate and sodium carbonate with small quantities of sodium chloride, sulfide, and sodium sulfite. Because of its hygroscopic nature, sampling to determine particle size distribution is difficult. A technique for precipitating a sample onto a copper mesh electron microscope target and subsequently counting the particles in various size ranges has been developed. The collected sample must be encapsulated in a protective atmosphere to prevent moisture pickup during transfer from the duct to the microscope. The mass median particle size for recovery furnace dust is around 1.9 microns. By count, the median size is about 0.4 micron.

Electron photomicrographs of the dust samples from recovery boilers show a change in the character of the dust depending upon operating temperature. At temperatures in the range of 350-360°F, the dust is primarily spherical particles. At a temperature of about 280-290°F, the dust contains large numbers of needle-like particles. These differences in particulate structure are thought to be the cause of the variations in the transporting and rapping properties of the collected dust.

Resistivity data for recovery furnace dust have not been reported extensively, primarily because high resistivity has not been identified as a problem.

Electrostatic precipitators for recovery boilers are of a variety of types including vertical and horizontal-flow types, wet and dry bottom types, and steel, tile or concrete shell types.

Dry bottom precipitators have been used extensively in recovery boiler precipitators from 1930 to 1948. In the dry bottom precipitators, dust from the collection plates was collected in pyramidal-type hoppers. The wet bottom precipitator was introduced to minimize problems associated with the collection, transporting, and redissolving of the collected salt cake. In the wet bottom precipitator, a solution of 50% liquor is pumped into the collection hopper. The collected dust is rapped from the plates and falls into the liquor solution, where it is dissolved and subsequently removed.

Current emphasis on odor control from kraft mills has resulted in a trend toward elimination of the contact between the flue gas and black liquor. Consequently, wet bottom precipitators may not be used on new kraft process mills. Also, elimination of the direct contact evaporators may influence the properties of both the gas and particulates to be handled by electrostatic precipitators.

Precipitators for recovery furnace boilers are designed for dust concentrations in the range of 1-9 gr/acf, with the bulk of the installations in the range of 2-5 gr/acf. Inlet temperatures range from 225-375°F, with the majority of installations operating at temperatures of 275-325°F. Gas velocities range from 2-8 ft/sec, with the largest number of precipitators operating in the 3-6 ft/sec range.

Connected input power for the majority of installations is in the range of 100-200 watts/1000 cfm. Design field strengths range from around 7-16 kV/in., computed as the ratio of average design voltage to plate spacing.

Design precipitation rate parameters for recovery boiler precipitators range from around 0.2 to 0.35 ft/sec.

Iron and steel industry. The application of electrostatic precipitators in the iron and steel industry has been in the cleaning of gaseous effluents from steelmaking furnaces, blast furnaces, foundry cupolas, sinter machines, and by-product coke ovens.

Steelmaking processes have undergone a number of changes in production methods. One of the earliest steelmaking furnaces was the Bessemer converter. About 1868, the open hearth process was invented and was the primary method of steelmaking for a number of years. The basic oxygen furnace, introduced around 1950, has increased in importance, and in 1969 about 40% of the total steel made was produced in BOF furnaces.

By-product coke

Production of metallurgical coke is made by the beehive process and in by-product coke ovens. The latter accounts for about 98% of all the metallurgical coke produced in this country.

Precipitators are used in the by-product coking process to remove the tars and particulate matter from the gases prior to recovery of the hydrocarbons.

The precipitator most often used for detarring is a cylindrical type consisting of collection electrodes made from 6-8 in. pipe, 6-9 ft long suspended from a header plate in a round shell. Discharge electrodes are suspended axially through the cylinders. The precipitators are maintained at a temperature high enough so that the collected tar drains from the plates and no rapping is required.

Three problems associated with the use of precipitators for cleaning coke oven gases are as follows: (1) Collection of the fluid tar makes electrical insulation difficult and requires that insulators be kept out of the gas stream. The insulators are also heated and cleaned on a regular scheduled basis. (2) The gases being cleaned are combustible when mixed with air, so that no inleakage of air must occur. Design often includes operation at positive pressure to insure no inleakage. (3) The gases can be corrosive. Protection against corrosion is provided by the film of tar on the interior surface of the collection electrodes. Spraying of tar on the exterior collection electrode surface can minimize corrosion at that point.

Coke oven gas precipitators are designed to handle gas volumes in the range of 5-15,000 acfm with efficiencies in the range of 95-98%. Precipitation rate parameters are about 0.2 - 0.3 ft/sec. Inlet loadings are in the vicinity of 0.5 gr/acf. Gas velocities average around 8 ft/sec, which is higher than for some applications since reentrainment is not a problem.

Power densities are 8-10 watts/ft^2.

Sinter plants

Sintering is a process for agglomerating iron-bearing fines to prevent their loss during reduction in the blast furnace.

The raw material is composed of iron-bearing fines, coke or coal dust, and a fluxing material such as limestone or dolomite. As the material moves through the sinter stand, it is ignited by surface burners and combustion is sustained by air drawn through the mixture by fans. The products of combustion are collected in a group of compartments called windboxes located beneath the grates of the sinter machine.

The particulate material emitted from the sintering process is a result of the mechanical handling of the raw material and combustion of the coal or coke. Under normal conditions, 5-100 lb of dust is produced per ton of sinter produced. Gas volumes vary from 100,000-450,000 cfm, with dust loadings of 0.5 - 6.5 gr/scf. About 80-90% of the particulate is greater than 20 microns. The dust contains fewer fines than metallurgical furnace operations. However, when preceded by a mechanical collector, the dust can be relatively small. Typically, the mass median diameter of the particles following a mechanical collector would be around 6 microns, whereas without a mechanical collector, the mass median diameter would be around 50 microns.

The electrical resistivity of sinter machine dust can vary radically depending upon the type and amount of fluxing material in the burden makeup. The amounts of fluxing material can vary from around 10-35%, and this variation can change the resistivity of the dust by several orders of magnitude. The very high resistivities associated with the higher percentages of fluxing materials can result in excessive sparking, lower operating voltage and power, and generally poorer precipitator performance.

The effect of the addition of the flux has not been fully explored; however, the condition is similar to that encountered in fly ash precipitators where limestone is added to the boiler for removal of sulfur oxides. It is postulated that the limestone reacts preferentially with the SO_3 present in the gases. Since the SO_3 is a secondary conditioning agent, surface conductivity would be decreased.

Studies of the mechanisms of conduction and possible corrective measures have not been explored for sinter machine precipitators to the same extent that they have for fly ash precipitators.

Design of sinter machine precipitators has conventionally been based on conditions in which resistivity has not been a problem. Because of the relatively large particle size of the dust, the range of design precipitation rate parameters has been from around 0.25 to 0.4 ft/sec. However, test precipitation rate parameters as low as 0.08 ft/sec have been obtained when high dust resistivity has been encountered.

Other design parameters for sinter machine precipitators are: gas velocity - 4-5 ft/sec, temperature - 250-300°F, electric field - 8-10 kV/in., average inlet dust loading - 1 gr/acf, and average precipitator power - 70 watts/1000 cfm.

Blast furnace

The effluent gases from blast furnaces have heating values of about 100 Btu/scf, which makes them valuable as a fuel for heating. The gas, however, contains particulate material carried over from the blast furnace and must be cleaned to prevent clogging of gas burners and gas mains. Electrostatic precipitators have typically been used for this service.

Blast furnace gas is usually passed through a dust catcher where the heavier particles are separated by inertial forces. From the dust catcher, the gas is passed to a wet scrubber and an electrostatic precipitator.

Precipitators for cleaning blast furnace gas are conventionally of the vertical-flow type employing cylindrical collection electrodes, although horizontal-flow, plate-type precipitators are also used.

Since the gas delivered to a blast furnace precipitator is cooled to saturation by the preceding wet scrubber, a wet type precipitator is used. Particulate removal is through a slurry hopper. The slurry is normally piped from the hopper to a dust disposal system.

The use of precipitators for cleaning blast furnace gases has generally followed the blast furnace production capacity. However, in recent years, the sales of blast furnace gas precipitators have been low compared with the peak periods during the 1940-1960 period.

Inlet gas temperature for blast furnace gas precipitators is low as compared with other applications. Typical temperatures are in the range of 70-100°F. Inlet dust loadings are also low, of the order of 0.05 - 0.3 grains/scfd for most installations.

Gas velocities are relatively high, around 6-15 ft/sec, since reentrainment is not a serious problem with wet precipitators. The average field strength (average voltage-to-electrode-spacing ratio) varies from around 9-15 kV/in. Input power ranges from 50-300 watts/1000 cfm.

Design precipitation rate parameters for blast furnace gas precipitators are around 0.2 - 0.4 ft/sec. Test data vary over a considerably wider range.

Open hearth

Open hearth steelmaking furnaces consist of a large refractory lined dish into which metal from the blast furnace, steel scrap, iron ore, and limestone is charged. Heat is provided by furnace burners which burn oil, natural gas or tar with combustion air that is heated in regenerative heat exchangers called checkers. Open hearth furnaces are often equipped with oxygen lances to facilitate oxidation of the carbon and other elements to be removed.

The particulate material carried out by the exhaust gases comes from a variety of sources, including dirt and other fines on the charge material, oil and grease, and volatile metal oxides from the scrap charge. During oxygen lancing, large amounts of iron oxide are evolved together with lesser amounts of nonmetallic oxides from the slag. The quantity of exhaust gases, particulate loading, and particulate composition varies widely during the period of the heat. Consequently, the precipitator input conditions vary depending upon operating conditions of the furnace.

The sizes of the particulate matter from open hearth furnaces range from less than 0.03 micron to several microns. Composite samples representing dust evolved during the entire heat indicate that 50% of the particulate is less than 5 microns. However, during the lime boil, the dust is considerably finer with as much as 77% less than 5 microns and 20% less than 1 micron. Resistivity of open hearth furnace dust varies with moisture, temperature, and composition.

Precipitators for cleaning open hearth gases are generally the horizontal-flow, duct-type with a steel shell. In large steelmaking shops, a multiplicity of furnaces are serviced by a common air pollution control system, which may consist of mechanical collectors, washers, and electrostatic precipitators singly or in combination. Open hearth precipitators are designed with precipitator rate parameters in the range of 0.15 - 0.3 ft/sec.

The total installed capacity of open hearth precipitators has steadily increased since 1950. In 1969, the total capacity reached approximately 12 million acfm.

Basic oxygen furnaces

The basic oxygen process of steelmaking utilizes high pressure oxygen introduced into the mouth of a basic, refractory lined converter to oxidize carbon and other elements from the charge. There is no external source of heat in the converter, and molten pig iron from the blast furnace constitutes the major constituent of the furnace charge. After charging, oxygen is blown into the converter at high pressure through a water-cooled lance.

Gas and dust emissions from BOF converters vary greatly with the stage of heat. During charging, the gaseous and particulate emission levels are low. During the oxygen blow, which may last for 20 minutes, large amounts of fume and gas are evolved. Gas volumes range from 200,000 - 1,200,000 cfm at temperatures of 3000 - 3200°F and may carry 300 lb/min or more of dust.

Fume from the basic oxygen furnace is composed primarily of iron oxide in amounts of 20-60 lb/ton of steel. Fume concentrations of up to 15 gr/scfm are produced under peak conditions. The fume is finely divided with most of the particles ranging from 0.1 - 1 micron in size, although on a weight basis, a considerable portion of the burden exists as relatively large particles.

Resistivity of BOF dust is a function of moisture content and temperature. Moisture comes from the evaporation of water in the cooling tower located between the precipitator and the furnace.

The cooling tower is an important part of the gas cleaning facility. It should be large enough to insure complete evaporation of the water to prevent carryover and subsequent clogging of the precipitator. Since the gas temperature varies, the rate of heat transfer varies, so that water quantities to the cooling tower must be controlled.

Precipitators for BOF gas cleaning are generally the horizontal-flow, duct-type with steel shells. Design precipitation rate parameters vary from around 0.15 - 0.25 ft/sec. The generally smaller particle size distribution accounts for the lower values of precipitation rate parameter.

Gas temperatures for BOF precipitators range from around 250-550°F depending upon design philosophy. Design efficiencies are generally 99+% for newer installations.

One problem associated with BOF precipitators is that the collection efficiency at the start of the oxygen blow is reduced. Cooling towers are generally set to operate the water sprays when the gas temperature reaches around 500°F. In the interim, dust resistivity is high and emissions from the stack can be relatively high during this period. The condition is called a lance puff and can be controlled by introduction of steam to condition the dust during the period before the cooling tower sprays come on.

Electric arc furnace

The electric arc furnace as used in the steelmaking process consists of a refractory lined structure with a dish-shaped bottom and a domed roof. Steel scrap, and perhaps hot metal from a blast furnace, are charged into the furnace and heated by an electric arc developed between graphite electrodes which are lowered into the furnace charge.

After meltdown, oxygen is introduced to remove the carbon and other elements. Oxygen sources can be from various sources including oxygen gas, oxides of alloying elements, iron ore, decomposition of limestone, etc.

The flue gases from electric furnaces contain large concentrations of carbon monoxide which must be converted to CO_2 prior to entering the precipitator to minimize the explosion hazard. This is usually accomplished by admitting air to the hot gas stream and allowing combustion to take place in the high temperature region. After combustion, the gases are passed through a cooling tower to reduce the temperature before entering the gas cleaning equipment.

The particulate emissions from electric arc furnaces average around 5-30 lb/ton of steel produced. The size and composition of the dust emitted from electric furnaces vary with the type and cleanliness of scrap and the metal refining procedure. Nonferrous impurities in the scrap can lead to significant quantities of oxide fumes. Also, presence of oil and grease in the scrap can produce large amounts of carbonaceous particulate matter during early stages of meltdown.

Dust from electric arc furnaces tends to be extremely fine. Data on particle size distribution vary. Some sources indicated that as much as 90-95% of the fume is below 0.5 micron. Other data would indicate a somewhat coarser dust.

Electrostatic precipitators have been used to clean electric furnace gases in the United States and Europe. However, the small size of the particles necessitates the use of a large precipitator to achieve high collection efficiencies, and other methods of cleaning electric furnace gases have been used to advantage in some instances.

Design precipitation rate parameters for electric arc furnace precipitators range from around 0.12 - 0.16 ft/sec.

Scarfing machines

Scarfing is the operation of removing the skin of the slab in the production of steel. In the scarfing machine, the slab passes under cutting torches which burn through the slab. The process generates iron oxide particles and fume which constitute an emissions problem. The application of electrostatic precipitators to this service is limited; the total capacity installed being around 500,000 cfm.

Cupolas

The iron cupola is used to provide a source of molten metal for cast iron foundries. The cupola is a refractory lined, cylindrical furnace which, when charged with pig iron, scrap, coke, and flue, provides a self-sustaining exothermic reaction to melt the charge and maintain it at the proper temperature.

Particulate emissions from iron cupolas consist primarily of oxides of iron, silicon, calcium, aluminum, magnesium, and manganese. The dust load in the effluent gases varies widely with ranges from 0.9 - 6.5 and 1.3 - 11 grains/scfm reported for cold and hot blast cupolas, respectively.

Particle size distribution of cupola dust varies between wide limits depending upon melt rate, type and cleanliness of scrap, and furnace operating conditions. Values range between 10% of the dust less than 10 microns to 40% less than 1 micron.

The gases from the cupola are high in carbon monoxide and must be burned prior to entering an electrostatic precipitator because of the potential explosion problem. Burning normally is accomplished by introduction of combustion air at the exit of the cupola. The combustion process can also burn carbonaceous particulates, and thus can have an influence on the particle size distribution as well as the composition.

Use of electrostatic precipitators on iron cupolas in this country has been extremely limited. Poor experience with operation of precipitators on a few installations has influenced the choice of dust collection equipment to a considerable extent. Also, the extreme variability of cupola operation resulting in extremely wide ranges of particle size and composition has tended to limit use of precipitators for this application.

Rock products. Electrostatic precipitators are used in the rock products industry in the collection of dust from cement kilns, gypsum kettles, and from auxiliary grinding, transporting, and handling operations.

Portland cement

Portland cement is produced by a wet or dry process which defines the conditions under which the ingredients are ground and fed into the calcining kiln. There are variations of these two production methods which are often termed semi-wet or semi-dry processes.

In the basic cement production process, the raw materials, consisting of lime, alumina, iron oxide, and a fluxing material are ground in a mill and introduced into a kiln. The material fed into the kiln is dried in the initial section, calcined as it passes down the kiln, and finally fused into a clinker in the final section of the kiln. The clinker is then removed, cooled, and ground to produce the final product.

The effluent gases from the kiln range from 40,000-100,000 cfm depending upon the type of kiln, method of gas cooling, and the method of preheating the raw materials. The gases are composed of nitrogen, water vapor, carbon dioxide, and small concentrations of oxygen and sulfur dioxide.

Particulate carried by the kiln gases originates from the abrasion of the charge as it tumbles through the kiln, the release of particulate due to the gas release associated with calcination, the ash from the fuel if the kiln is coal fired, and the fume resulting from the vaporization and condensation of alkali. The particles resulting from the mechanical abrasion are generally large in comparison with those produced by alkali condensation.

Resistivity of cement-kiln dust is dependent upon moisture content and temperature. In the range of 500°F and above, resistivities are generally in the range suitable for collection by electrostatic precipitators regardless of moisture. However, from 300-400°F, resistivities are extremely dependent on moisture content. In the wet process kiln, moisture is provided by the evaporation of the water from the slurry feed to the kiln. In the dry process, moisture must be provided by evaporation of water in the cooling tower.

Electrostatic precipitators used on cement kilns are of the horizontal-flow, duct-type with insulated steel shells. The application of precipitators to control of cement kiln dust has steadily increased over the past 50 years; the present installed capacity being around 40 million acfm. The trend in the application of precipitators is toward a higher collection efficiency; the average for the past five years being designed for around 99.7%.

Inlet dust loadings for cement kiln precipitators vary from a minimum of around 3 gr/scfd to around 50 gr/scfd. Gas velocities range from around 3-8 ft/sec. Moisture contents range from 4-14% for dry process kilns to 13-40% for wet process kilns. Inlet gas temperatures range from 350-650°F on wet process kilns to 500-700°F on dry process kilns. Precipitation rate parameters for cement kilns range from around 0.25-0.45 ft/sec.

Precipitator applications to cement kilns have been particularly favorable from the standpoint of recovery of cement as well as air pollution control. The effluent dust from the cement kiln has about the same composition as the kiln charge. Consequently, its recovery is of direct economic importance. However, alkali present in the dust cannot be recycled. A fundamental property of the electrostatic precipitator is that larger particles tend to be separated first, and the smaller, alkali-containing fraction of the dust tends to be removed in the last stages. This fractionating effect has been used to separate the dust that is relatively free from alkali and to recycle it through the kiln.

There are several problems associated with the use of electrostatic precipitators in cement kiln applications. (1) In the dry process kilns, the moisture content is low, and consequently resistivity would tend to be high in the temperature range of 300-400°F. There is a trend toward the use of fabric filters on dry process kilns in this country. (2) Upsets in kiln operation can create conditions under which combustible gas can be introduced in the precipitator. Instances of fire in the precipitator have been reported which limit acceptance of precipitators, although this can also be a problem in other types of dust control equipment. (3) Operation at certain temperatures can result in a deposit on the electrodes that impairs precipitator performance.

Gypsum

Gypsum is a hydrated calcium sulfate which, when heated, looses water to form plaster. Removal of the water occurs in a process called cooking. Electrostatic precipitators are used to control emissions from gypsum kettles.

Particulate emissions from the cooking process result from the calcination process and the mechanical agitation of the charge. The size of the dust particles is relatively large compared with processes where the vaporization and condensation of material occurs.

The process of cooking increases moisture of the exit gases. The wet gas is mixed with ventilating air and flue gas to give a mixture of gas that ranges from 300-400°F with a moisture content of 30-35%. As a result of the moisture, resistivity of the dust is not usually a problem. However, at times, water sprays are used in the flue ahead of the precipitator.

The use of electrostatic precipitators in the production of gypsum has steadily increased from around 1935 to the present. The total installed capacity is approximately 1.8 million acfm. The gas flow ranges from a minimum of around 3000 acfm to 14 acfm for kettles to a maximum of around 80,000 acfm for rotary calciners. Efficiencies are generally in the range of 95-99+%. Gas velocities range from 1.5-8 ft/sec. Inlet dust loadings are from around 4-60 gr/scfd. Inlet gas temperatures are around 200-350°F for calciners and 125-250°F for rock dryers. Design precipitation rate parameters for precipitators used in the gypsum industry are around 0.4 - 0.5 ft/sec.

Chemical industry. Precipitators are used in the chemical industry in the production of sulfuric and phosphoric acids.

Sulfuric acid

Sulfuric acid is made by the oxidation of sulfur dioxide to sulfur trioxide and subsequent absorption in a recirculating sulfuric acid solution to make acid of the desired concentration. About 95% of the sulfuric acid produced in this country is by the contact process in which SO_2 is catalytically oxidized by atmospheric oxygen in the presence of a vanadium pentoxide catalyst. Sources of SO_2 for the process are burning of elemental sulfur, roaster gases from metallurgical operations, and burning of hydrogen sulfide and spent acid from petroleum refineries.

Electrostatic precipitators can be used in the manufacture of sulfuric acid in two ways. If the source of SO_2 is smelter gas from nonferrous metallurgical operations, the gases contain approximately 3-10% SO_2 and are contaminated with dust, which must be removed prior to being introduced to the converter to prevent fouling of the catalyst. Cleaning can be accomplished by electrostatic precipitators or wet scrubbers.

In the converter, SO_2 present in the gases is converted to SO_3. Gases from the converter exit at around 450°F and pass to the absorber where the SO_3 combines with water to produce 98-99% sulfuric acid.

Gases leaving the absorber contain unabsorbed SO_3 and H_2SO_4 mist. The mist is of very small size and will pass through the absorber without being collected and would be emitted from the process unless suitable collection equipment is provided.

The type of collection equipment needed to remove the acid mist depends upon the size of the particles. Wire mesh eliminators have collection efficiencies of over 90% when most of the particles are greater than 3 microns, which is the case when 98% acid is being produced. When oleum is also produced, 85-95% of the particles leaving the oleum tower is less than 2 microns and wire mesh pads may not effectively remove these fine particles. Electrostatic precipitators have been extensively used for acid mist removal and are effective for the smaller sizes.

Precipitators for acid mist collection have historically been of the vertical up-flow type with cylindrical shells constructed of sheet lead supported by steel banding. Discharge electrodes are of lead with a star cross section. Acid mist precipitators with all-steel construction have been installed in recent years without apparent difficulty.

Between 1945-1969, about 120 sulfuric acid mist precipitators were installed with a total capacity of 2,230,000 cfm. The average precipitator size has increased from 10,000 acfm in 1945 to around 30,000 acfm in the 1964-1968 period. Design efficiencies are in the range of 97.5 - 98.5%.

Gas velocities for acid mist precipitators range from 2-8 ft/sec, with the majority falling in the 3-5 ft/sec range. Inlet loadings range from about 0.2 - 2.5 gr/scf. Operating temperatures range from 80-180°F. Input power varies from around 150-700 watts/1000 cfm for the majority of installations. Design field strengths are from 8.5 - 13 kV/in. Design precipitation rate parameters are around 0.2 - 0.3 ft/sec.

Phosphorus

Precipitators are used in the production of phosphorus and phosphoric acid. In the production of phosphorus, phosphate rock, silica and coke are charged in an electric furnace and heated to around 2300-2700°F to liberate P_2O_5, which is reduced to elemental phosphorus by the carbon. The effluent from the furnace is cleaned by an electrostatic precipitator operating above the condensation temperature of the phosphorus (525-620°F) to prevent dust contamination of the phosphorus as it is condensed. Precipitators typically remove 90-99% of the dust.

Precipitators for use in cleaning phosphorus furnace gas are typically vertical gas flow, single-stage types with cylindrical collection electrodes. The collection electrodes are heated to avoid phosphorus condensation and special rappers are often used to avoid damage during rapping.

Special types of hoppers are used for dust removal since the collected dust contains some absorbed elemental phosphorus which ignites on exposure to air.

During 1938-1969, about 20 precipitators have been installed for hot phosphorus applications. The total gas volume handled is around 165,000 acfm. Gas velocities for phosphorus precipitators range from 1-6 ft/sec, with the average around 2-3 ft/sec. Average gas temperatures range from 500-600°F, with some as high as 800°F. Dust loadings range from 4-15 gr/scf, with the majority in the range of 12-14 gr/scf.

Predictions for phosphorus furnace applications are for continued growth, although the total volume is small in comparison with other areas.

Precipitators for use in the production of phosphoric acid are for mist elimination. During 1930-1960, the cumulative installed capacity was around 150, 000 acfm.

The corrosive nature of the gas creates some problems in the choice of materials. Stainless steel pipes of 5-15 inch diameter are used as collection electrodes. The collected mist drains from the plates so that no rapping is required.

Inlet gas velocities for phosphoric acid mist precipitators range from 2-8 ft/sec. Inlet gas temperatures vary from 150-300°F, and inlet concentrations range from around 5-35 gr/scfd.

Carbon black

Precipitators used in the collection of carbon black are for the purpose of agglomeration of the particles so they can be collected in a mechanical collector. About 18% of the carbon black is collected in the precipitators and 72% in the mechanical collector. Bag filters are often used following the mechanical collectors to reduce the emissions to the atmosphere.

Carbon black particles are extremely fine, ranging from 0.02 - 0.4 micron. The conductivity is also very high, so that the particles would tend to be discharged upon contact with the collection electrode. However, the carbon black particles cling tenaciously to both the discharge and collection electrodes and cleaning is a problem.

It is estimated that about one hundred sets of electrostatic precipitator - mechanical collector units have been built since 1926. No information was found on installations made since 1958.

Municipal incinerators. Use of electrostatic precipitators for control of municipal incinerator emissions is a relatively new application in this country, although the practice is rather widespread in Europe.

There are two principal types of furnaces in general use for incineration of municipal wastes—these are water-cooled and refractory lined furnaces. The type of refuse handled is highly variable between countries and between different sections of the same country. This leads to large variations in the properties and composition of the particulate.

Particle size of the fly ash from municipal incinerators ranges from a mass median diameter of 15 to 30μ. Resistivity of the ash varies with temperature and moisture content and with particle size.

Gases from municipal incinerators are at temperatures in the neighborhood of 1200-1800°F and must be cooled before entering the precipitator. Cooling can be provided by evaporation of water in a water cooling tower or by heat exchangers in a system utilizing heat recovery.

Design precipitation rate parameters for a group of precipitators installed on European incinerators range from around 0.2 - 0.4 ft/sec. Gas velocities range from 2-4 ft/sec. Power densities range from 50-200 watts/1000 cfm.

Precipitation rate parameters for European precipitators vary with precipitator inlet gas temperature. Data from the U. S. installation, for which information was available, agree well with those data from the European installations.

No test data are available on the municipal incinerators in this country since they have been installed so recently.

Petroleum industry. The principal uses of electrostatic precipitators in the petroleum industry are in the collection of particulate emissions from fluidized bed catalytic cracking units and the removal of tar from various gas streams, such as fuel gases, acetylene, and shale oil distillation gases. The first of these areas, recovery of catalyst dust, originated with the production of high octane gasoline during World War II. Electrostatic precipitators were used to recover catalyst from the discharge stream of the catalyst regenerators as a part of the process. Improvements in mechanical collectors inside the regenerators have eliminated the process requirements. However, precipitators are presently used for control of dust emissions from the process.

Gases from the catalyst regenerator are exhausted from the top through a series of mechanical collectors which return all but the fine particles to the process. The regenerator may be followed by waste heat boilers that recover some of the energy and reduce the temperature of the gases to the precipitator to around 600-700°F.

The inlet dust concentration varies with the type of mechanical collector. A typical range is 0.2 - 1.0 gr/scfd. Mass median particle size is around 10-12 microns. Resistivity varies with temperature and moisture content. Conditioning of the catalyst dust by additions of ammonia to the effluent has been reported to reduce resistivity and improve performance in instances where high resistivity dust has been a problem.

Detarring

Precipitators used for detarring of gases are commonly of the single-stage, vertical wire and pipe type, with collection electrodes suspended from a top heater. The collected oils and tars are usually free flowing and no rapping is required for removal.

During the period 1940-1963, approximately 55 precipitators were installed for detarring of carburetted water gas, 3 for detarring oil gas, 3 for reformed gas, 2 for shale oil, and 1 for acetylene. The total gas volume for all of these applications is around 400,000 acfm. Gas temperatures for detarring precipitators range from around 70-120°F and collection efficiencies are around 95%.

The total market for detarring precipitators is small since very little manufactured gas is sold in this country and the requirements for shale oil processing and acetylene manufacturing are relatively small.

Nonferrous metals. The commercial use of electrostatic precipitators has been standard practice by copper, lead, and zinc smelters in cleaning the off-gases from the extraction process. Precipitators are also used in cleaning gases from electrolytic cells in the reduction of bauxite to produce aluminum.

Extraction of nonferrous metals from their ores is carried out in a number of types of processing equipment, many of which are common to all nonferrous operations.

Sinter machines are used to convert metallic ores, fines, and plant process dust into larger material that can be handled in the reduction process. Pellets to be sintered are spread on grates that move the material through the sinter machine. Gas-fired burners ignite the material and air is supplied by fans to maintain combustion. Exit gases are collected in windboxes and passed to the electrostatic precipitator for cleaning.

Ore roasting can be accomplished in a variety of types of furnaces including multiple hearth, flash roasters, and fluid bed roasters. Smelting and refining operations are carried out in reverberatory furnaces and blast furnaces. Converters are used to convert matte to metallic copper. Cupolas are used in the nonferrous metals industry to melt and reduce copper brasses, bronzes, and lead.

Aluminum is produced by the electrolytic reduction of alumina (Al_2O_3) dissolved in a molten cryolite bath. During reduction, electrolytic, thermal, and chemical action in the cell results in the evolution of carbon and alumina dust, other particulates, and gaseous fluorides. Hoods over and around the cells collect the effluent which is sent to mechanical collectors followed by an electrostatic precipitator and then to a scrubber for removal of the remaining gaseous fluorides.

In copper production, the copper-bearing ores are roasted to eliminate some of the sulfur from the concentrate and to volatilize zinc, arsenic, and antimony present in the ores. The roasted ores are then smelted to produce a molten sulfide of iron and copper. The copper matte from the smelter is then converted to copper by blowing it with air in a converter. The blister copper from the converter is then refined by either fire or electrolytic methods.

Lead production begins with either oxide or sulfide ores. Oxide ores can be directly reduced in a blast furnace, whereas sulfide ores must be first converted to oxides. This is accomplished by roasting or sintering in an oxidizing atmosphere. After converting to the oxide, the lead ore is reduced in a blast furnace by reaction with carbon supplied by coke charged in the furnace. Refining of the lead is accomplished by electrolytic refining or by a kettle or reverberatory furnace.

Zinc

Zinc is generally extracted from ores containing both zinc and lead sulfides, although some zinc and copper-zinc ores are processed. The zinc ores are concentrated by flotation and processed in a roaster to convert the zinc sulfides to zinc oxide. Metallic zinc is produced from the roasted ore by retorting, electrolysis or fractional distillation.

Most of the electrostatic precipitators used in the nonferrous metals production have been designed by the large western smelters, and hence information on the applications in the nonferrous metals industry is limited. Information that is available indicates that design precipitation rate parameters vary from 0.05 - 0.07 ft/sec for precipitators operating on converter gas, 0.12 - 0.14 ft/sec for precipitators used on copper roasters and reverberatory furnaces, and around 0.25 ft/sec for sinter machine precipitators.

High temperature, high pressure gas cleaning. A unique application of precipitators would be in the cleaning of high temperature, high pressure gases. One of the early applications of precipitators was in the removal of ash from the products of high temperature gasification of coal. This work was a pilot-scale research operation conducted in conjunction with the development of the coal-fired, gas-turbine locomotive. Temperatures of 1500°F and pressures up to 600 lb/in.^2 were used in this study.

Current interest in high temperature, high pressure gas cleaning is for the use of the gases produced from waste incineration to produce electric power from gas-turbine-driven generators.

Research has been conducted on corona generation at temperatures up to 1700°F and pressures of 100 psig. Precipitation rate parameters of 0.23 - 0.26 ft/sec were obtained on pilot-scale units and extrapolations made to full-scale precipitators.

New application areas. New applications for electrostatic precipitators can take the form of replacement of other types of dust control systems, or the control of particulate emissions from sources where no particulate control devices are now used.

The major advantages of electrostatic precipitators are that high collection efficiencies can be achieved even with small particles and the pressure drop across the precipitator is low. The latter characteristic makes precipitators especially attractive when large gas volumes are to be handled.

The high initial cost of electrostatic precipitators is a disadvantage. However, when determining air pollution control costs, total costs over a period of years should be determined.

Two factors that limit application of electrostatic precipitators are: (1) high resistivity dust results in limitation of the operating voltage and current so that the resulting precipitation rate parameter is low. This necessitates the use of an excessively large precipitator, alterations in inlet gas temperature, or additions of chemical conditioning agents to alter dust resistivity. These constitute additional costs and can make other dust control methods more attractive. (2) Very fine particles do not acquire a charge sufficient for good precipitation. This again results in low precipitation rate parameters requiring larger precipitators with higher costs.

Two primary areas for increased precipitator applications are in the control of emissions from municipal incinerators and in control of foundry cupola emissions. The use of precipitators on municipal incinerators is relatively common practice in Europe. Within the past year, several installations have been made in this country.

The control of cupola emissions by electrostatic precipitators is potentially a promising area. However, details of accommodating the highly variable emission rates and character of the emissions must be resolved.

A summary of the use of the various types of dust control equipment in each of the areas identified by SIC classification for the 1966-1967 period is given in Part II of the manual. These represent potential use areas for electrostatic precipitators.

Research and Development Recommendations

Based on the precipitator systems study, a research and development program has been prepared to provide additional fundamental information on precipitator technology and applied research aimed at resolving some of the problems found that limit precipitator performance and hence their application to various dust control problems.

The program is divided into two broad areas covering a plan for basic research and a plan for applied research. The applied research program is further divided into research directed toward collection of dusts with high electrical resistivity, collection of fine particles or fume, and general application problems.

In addition to these defined areas, provision was made in the program for investigation of new precipitator concepts and for studies of electrostatic augmentation of other types of dust control equipment.

In addition to the technical research areas, provision was made for a critical review and analysis of the methods of specifying precipitators for specific applications and for the most appropriate type of contract for the purchase of precipitators. The latter should encompass the negotiated type of contract, which has been used by some electric utility companies and the penalty-bonus contracts that have recently been employed. Finally, performance guarantees should be reviewed, especially in regards to the methods of acceptance testing and the desirability of delayed acceptance tests.

Table 3 lists the suggested research plan. The research topics are listed for a five year research effort. Man hours are shown for a program of approximately five million dollars over the five year period. The contract calls for two research plans, one for five million and the other for a seven million dollar expenditure over the five year period.

For the seven million dollar program, it is recommended that the additional funds be used during the fourth and fifth years for demonstrations of the effectiveness of the research programs in full size plant operations. This may require design and building of precipitators or at least substantial modifications, so that funds will be required for purchase of components and for construction and modification.

Table 3

Research and Development Plans

BASIC RESEARCH PLAN

Year 1	Man-Years	Year 2	Man-Years	Year 3	Man-Years	Year 4	Man-Years	Year 5	Man-Years
Refine system model to include diffusion charging, gas velocity distribution, reentrainment, sparking and back corona limitations	5	Model verification with pilot and full scale installations	5	Upgrade model to include data from related studies, field test data, and further theoretical studies	3	Optimization of parameter design utilizing model studies of reliability of design with model	3	Field tests	5
Fundamental studies of mechanisms of conditioning - factors influencing formation of SO_3 - rates of adsorption	3	Kinetics of surface reactions in conditioning process	3	Study of alternative conditioning agents	2				
		Determination of role of electric wind and turbulence in particle collection	2	Analysis of collection efficiency in terms of particle concentration and remixing by electric wind and other turbulence	2				
		Studies of mechanism of spark propagation	2	Relationship of sparking and development of power arc as related to power supply characteristics and degree of sectionalization	2	Study effect of voltage waveform on sparkover voltage	2		
Fundamental studies of reentrainment Quantitative relationships between resistivity - gas velocity - particle adhesive and cohesive forces	3		3	Verification of reentrainment relationships on full size precipitators	3				
						Effects of deposits on discharge wire on corona quenching	2		
Evaluation of new precipitator concepts - electrostatic augmentation	4		4		4		4		4
				Theoretical study of corona suppression by space charge from small particles and methods of increasing corona current	2				
						Study of corona conditions at high temperatures and pressure	3		

Table 3 (continued)

APPLIED RESEARCH PLAN

Collection of High Resistivity Dust

Year 1	Man-Years	Year 2	Man-Years	Year 3	Man-Years	Year 4	Man-Years	Year 5	Man-Years
		Review of high temperature fly ash precipitator operation - identify problem areas with existing plants	2	Investigate potential problems with high temperature fly ash precipitators - potential for fly ash sintering, effects of gas velocity on reentrainment at high temperatures, gas viscosity - changes in V-I characteristics of gas, etc.	3	Review economics of high temperature fly ash precipitator operation	2		
Investigate potential for corrosion and fouling of air heater at low flue gas temperatures	2	Review economics of low temperature operation including increased boiler efficiency and increased maintenance costs, if any	2	Review of experiences with low temperature operation of precipitators	2	Pilot scale studies with low temperature precipitators	3		
		Analysis of operation of fly ash conditioning plants	2	Review of potential for conditioning of high resistivity dusts other than fly ash	2	Pilot and full scale tests of conditioning	4	Pilot and full scale tests of conditioning plants	5
				Study precipitator design for handling high resistivity dusts	3	Pilot studies of modified precipitator	4	Full scale field installation	10
				Collection of Small Particles and Fumes					
				Analysis of methods for increasing charge on small particles and fumes, or for agglomerating particles	3	Pilot plant studies of precipitator designed for fine particle collection	4	Field trials of small particle precipitator	4

Table 3 (continued)

Application Problems

Year 1	Man-Years	Year 2	Man-Years	Year 3	Man-Years	Year 4	Man-Years	Year 5	Man-Years
		Study effects of odor control methods of design and operation of precipitators for pulp and paper recovery boilers	3	Investigate methods of combatting "snowing" from recovery boiler precipitators	3				
						Analysis of the impact of control of gaseous pollutants on application of electrostatic precipitators	4	Comparison of the the economics of combination low energy scrubbers and electrostatic precipitators with high energy scrubbers for both gaseous and particulate control	4
		Study of high resistivity problems in sinter machine precipitators	2	Study economics of dust control on foundry cupolas and review potential for electrostatic precipitators in this application	3	Review methods for improved precipitator operation on intermittent metallurgical processes. Potential for rapping during periods of heavy dust loading			
				Analysis of methods of combatting the high resistivity problems associated with dry process kilns	2	Analysis of fire and explosion hazards associated with electrostatic precipitators operating on cement kilns and methods of combatting these problems	2	Review of sulfate buildup on cement kiln precipitators	2
								Review of problems of ash handling from hoppers	3
		Review and analysis of the procedures for specification of electrostatic precipitators. Review of contracting procedures and of methods of establishing performance guarantees - applicability of penalty-bonus clause	5	Review and analysis of methods of bid analysis	2				
Total	17		35		41		37		37

The following discussion is a further amplification of the suggested research topics listed in Table 3.

Basic Research Plan

The basic research plan is intended to define limitations of precipitator performance and to obtain information that can provide a more rational basis for design. The following topics are suggested.

Refine system model. A simplified system model was developed under Contract CPA 70-166. This model was a first step in showing interrelationships between the variables that influence precipitator performance. However, several important relationships were not included. These include (1) diffusion charging, (2) effects of gas flow distribution, (3) limitations due to sparking which defines current-voltage relationships, and (4) reentrainment effect. The program is designed to include the effect of these variables in the overall model. The second year's effort would include verification of the model on pilot and full scale units. The third year's effort would include upgrading of the model to more accurately predict performance of field precipitators. The data for upgrading would be provided from carefully conducted field tests and from quantitative relationships developed under other research programs. The fourth year's effort would involve optimization of precipitator design based on studies with the mathematical model. Optimization might include variations in current-electric field, resistivity, and gas velocity to give the best efficiency of collection. The fifth year's effort would be further field tests to verify the optimization conditions.

The objectives of the model study would be (1) to determine whether a better basis for design can be developed based on theory as opposed to the empirical methods currently used, (2) to provide a method for analyzing the problems of a particular installation where poor performance is being experienced, and (3) to provide a convenient method for analyzing the interaction of precipitator, dust, and gas variables, and to permit optimization of these variables in a systematic approach.

Role of turbulence and electric wind. Controversy exists as to the effect of turbulence and the electric wind on precipitator performance. Since, in a turbulent flow condition, collection occurs only within the boundary zone, the transport of the dust to the boundary zone must be by means of gas turbulence or particle diffusion. Collection efficiency is related to the ratio of the dust concentration within the boundary layer and that in the interelectrode space. Thus, if there is a variation in the dust concentration brought about by gas turbulence, or other factors, the efficiency equations would be altered.

The magnitude of the electric wind has been determined by a point plane apparatus with large current flows. Also, studies have been made of the potential of the corona process to serve as a means for moving air. However, there is still considerable uncertainty regarding the magnitude of the electric wind in commercial precipitators and its influence on collection efficiency.

Fundamental studies of spark propagation. The voltage and current relationships in a practical precipitator are limited by sparkover. The thickness of the dust layer, the resistivity of the dust layer, and the magnitude of the electric field at the dust surface influence the voltage at which sparking occurs. In analysis of precipitator performance, quantitative relationships are needed to establish the voltage and current at which a precipitator will operate for a given set of dust conditions. Further studies are also needed to quantitatively establish conditions for spark quenching. Effects of power supply size, sectionalization, etc., are needed to give a firm basis for design of energization equipment.

Equivalent circuits of precipitators and power supplies should be developed to permit rapid evaluation of the effects of charging parameters on sparking and spark quenching. Finally, studies are proposed to show the effects of the rate of voltage rise on the peak and average voltages that can be attained for a given spark rate. The latter is significant in terms of the interest in pulsed power supply operation.

Reentrainment. Studies of rapping requirements have so far been limited to various types of dust with power on and power off. Since the force holding dust on the collection plate is so much a function of the electric field strength, rapping requirements should be related to the basic holding force. Too intense rapping can result in significant reentrainment, and since the holding force is a function of resistivity, there would be a tendency for low resistivity dust to be easily reentrained by too severe rapping.

Also, little work has been done on relating rapping requirements to the condition of the dust. Dusts can vary from light fluffy conditions to wet sticky conditions as a result of gas temperature and composition. Wet sticky dust can be difficult to remove by normal rapping techniques.

Little attention has been given so far to the collection of medium-to-low resistivity dusts as a function of gas velocity. There is considerable evidence to indicate that low dust resistivity can result in excessive reentrainment of the dust layer, as well as higher losses during rapping. Quantitative data are needed to relate reentrainment to dust resistivity so that conditions of optimum resistivity and gas velocity can be determined.

Effect of dust layer on corona generation. The presence of deposits on the discharge wires appears to have varying degrees of influence on precipitator performance. In some instances, corona current suppression occurs, whereas in other instances, normal precipitation appears to occur even with reasonably large buildup on the discharge wire. The effect appears to be related to the tightness of the deposit, resistivity of the deposit, and evenness of the deposit.

High temperature corona. Use of electrostatic precipitators for cleaning of gases at temperatures above around 100° F is a unique application. Because of increased thermionic emission from the discharge electrode at elevated temperatures, sparking occurs in negative corona at reduced voltage. Further studies are needed in the definition of the most desirable conditions for corona generation at temperatures above around 1500°F and pressures around 100-200 psi.

Collection of small particles. Research should be directed toward the improved collection of small particles by electrostatic precipitators. Because of the inherently lower charge that can be applied to a small particle and the resulting lower precipitation rate parameter, techniques for enhancing the charge on small particles should be investigated.

The small particle problem is especially important in the collection of metallurgical fume. Charging particles of less than around 0.3μ diameter occur primarily by diffusion charging. Methods of enhancing the charge by this mechanism should be studied. It has been shown that the effect of electric field on diffusion charging is to increase the charging rate. Also, increased ion densities would increase the charging rate. Studies should include methods for minimizing space charge suppression of the corona and for agglomerating the particles.

High resistivity problems. High dust resistivity limits the current and voltage at which precipitators can operate and reduces the efficiency of collection. Since many industrial dusts are in the high resistivity region, techniques must be developed for handling these dusts. These techniques include modifications to the basic precipitator, use of larger collection surface areas or modification of the dust resistivity. Dust resistivity can be modified by increased gas temperature to enhance volume conductivity, reduced gas temperature to enhance surface conduction or by increased moisture or secondary conditioning agents to enhance surface conduction.

Low temperature operation. Operation of electrostatic precipitators at gas temperatures below around 260-270°F is an alternative method of reducing resistivity. Experience has shown that efficiencies can be substantially improved by reducing the flue gas temperature when a precipitator is limited by high dust resistivity. High dust resistivity is normally associated with low sulfur coals in the case of fly ash precipitators.

There is concern that low gas temperatures can result in excessive corrosion of the air heaters. However, many installations are functioning at reduced gas temperatures even with high sulfur coal.

Further research is needed to define the conditions under which corrosion becomes excessive, especially when burning low sulfur coal. Problems of control of the temperature to minimize excessive temperature excursion should be identified.

High temperature precipitation. Operation of fly ash precipitators ahead of the air heater is a potential method of reducing fly ash resistivity. Experience with electrostatic precipitators in other applications in which gas temperatures are in the range of 500-600°F would indicate that the basic precipitator can function without difficulty in this temperature range. Studies of the economics of high temperature operation should be made to determine the comparative costs of this alternative to the high resistivity problem. Analysis of operating problems with high temperature precipitators should be made to determine the possibility of fusing of the fly ash or other factors that can influence the choice of this method of dust control.

Dust conditioning. The role of conditioning agents in influencing resistivity of the dust needs further study. Where secondary conditioning agents are effective, as in combustion processes, the relationships between fuel properties and the amount of conditioning agents should be resolved. Also, the mechanism by which the conditioning agents act to influence resistivity should be explored. The influence of dust composition on the action of the conditioning agent should be investigated.

Studies should also be made of the influence of artificial conditioning agents on the resistivity of various types of dusts. The majority of work on conditioning has been on fly ash from electric power boilers and petroleum catalytic crackers. The application to other types of dusts should be explored.

Precipitator modifications to handle high resistivity dusts. Studies should be made of the voltage-current requirements in a precipitator to determine the optimum conditions for handling high resistivity dusts. These studies should relate charging time and electric field requirements for optimum performance.

Application problems. Several problems have been noted which relate to the application of electrostatic precipitators in specific areas and to the overall acceptance of precipitators. Suggested research on these problems are grouped together in the suggested research plan.

Pulp and paper industry

Application of precipitators in the pulp and paper industry has been in the control of emission from black liquor recovery boilers. Recent interest in the control of odor emission from paper mills has changed the recovery process to eliminate the contact between black liquor and flue gas. Effects of these changes on precipitator operation is an area that needs further study and definition.

A problem with recovery boiler precipitators has been the periodic release of light fluffy particles from the precipitator. The effect is termed "snowing" and creates problems with corrosion in the area immediately surrounding the plant. Methods are needed to prevent the occurrence of this problem.

Electric power generation

Collection of fly ash from electric power generation plants is the largest single application of electrostatic precipitators. Current activity in the use of wet scrubbers to control SO_2 emissions, methods of removing sulfur from the fuels, and control of NO_x emissions can influence the application of precipitators in this important area. Since scrubbers are currently being considered as a means of SO_2 control, the question of the effectiveness of using high energy scrubbers for removal of particulate as opposed to the use of precipitators with low energy scrubbers should be resolved.

Metallurgical industry

Electrostatic precipitators have historically been used for collection of dust emissions for sinter machines used in the processing of fines from the iron and steelmaking operation. However, use of high percentages of lime has resulted in high resistivity dust which has greatly reduced the effectiveness of precipitators for this application. Further research is suggested to find means for conditioning the dust or other ways of combatting the problem.

Use of precipitators for collection of foundry cupola dusts has been a promising new area of application. Review of the cost factors involved in the collection of foundry cupola dusts with various dust control methods should be made. Potential for use of precipitators should be explored, especially if methods of overcoming the small particle and high resistivity problems can be developed.

Some metallurgical problems are intermittent, which provides the opportunity for more intense rapping during the off periods. This offers the promise of starting with clean plates with perhaps no plate rapping during peak dust load periods. The technique may improve overall efficiency of operation.

Cement industry

Use of electrostatic precipitators for control of emissions from cement kilns is limited by (1) the high resistivity of the dust from dry process kilns, (2) history of fires and explosions in cement kiln precipitators, and (3) buildup of sulfate on the electrodes at certain operating conditions. The high resistivity problem has been a factor in the decline in use of precipitators or dry process kilns in this country. Successful methods of combatting this problem would enhance the use of electrostatic precipitators in this application.

Fires occur in cement kilns due to upsets in the kiln which result in combustible gases being released from the kiln. The condition can occur during start-up or during operation when a combustible mixture is formed by introduction of air following the kiln.

The problem with fire in the dust collection equipment is not limited to precipitators, but is made more severe by the presence of ignition sources resulting from sparking within the precipitator.

The problems with fire in the precipitator are largely due to operating procedures, but their occurrence limits precipitator application in this area.

The buildup of sulfate deposits on the discharge wire and collection electrodes of cement kiln precipitators is apparently the result of operation within certain critical temperature regions. However, difficulty has been noted with precipitator operation due to the sulfate buildup. Resolution of the problem would enhance operation of cement kiln precipitators and increase their use in this area.

Many precipitator operating problems are due to improper ash removal. Clogging of the ash removal system can cause the precipitator to be shut down for short periods. Failure of the ash removal system can also result in excessive sparking or arcing of the precipitator. Formation of a fused fly ash mass can result which causes further ash removal problems. A condition called "concreting" of the ash can result if a damp ash is encountered.

A better definition of the ash handling problems, relationships for sizing ash handling systems, and operating conditions for optimum performance are required.

Review of Specification and Contracting Practice

The study of the application of precipitators indicates the desirability of a review of procedures for specifying, bid evaluation, and contracting procedures. Such a review would be of benefit to both precipitator manufacturer and user. Specifications are often too loose so that there is no firm basis for fair competitive bidding. When low bids are accepted, the precipitator design is often too marginal to perform adequately except under ideal conditions.

Current air pollution legislation is imposing more strict limitations on particulate loadings. This has resulted in efforts on the part of the users to impose more severe penalties for failure to meet design specifications. The penalty-bonus type of contract has been used in an effort to insure adequate performance. However, experience with this type of contract is limited, and the desirability of this type contract has not been established.

The main goal of this proposed study is to arrive at the most desirable method of specifying and contracting that will give adequate assurance of performance and minimize the tendency to provide a precipitator whose performance is marginal.

Performance testing practice to determine whether a particular installation meets contract guarantees also needs review. Desirability of two-step testing, one following completion of the installation and a delayed test, should be investigated. This practice is followed in other countries and appears to have merit in insuring long-term reliability.

Submitted by:

Sabert Oglesby, Jr., Director
Engineering Research

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